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particular sensation, remaining so for a length of time depending on the wave length of the fatiguing color. The recovery of the retina was most rapid from the red and least from the violet. By this method, Burch confirmed the fundamental color sensations of the Young-Helmholtz theory, but in addition claimed evidence for believing blue to be a fourth sensation.

It was suggested to the writer that a combination of this method with that of Ferry would probably lend itself to a more conclusive determination of the fundamental color sensations.

Description of Apparatus and Method of Observation.

The apparatus consisted of a Browning two-prism spectrometer, a small motor with a disc attached, and an arrangement for registering the speed of the latter. An acetylene flame in a "Perfection" burner was the source of light, which gave a brilliant spectrum of considerable dispersion. The gas was supplied to the burner at a constant pressure. As the rotation of the disc caused air currents which disturbed the flame, it was found necessary to place the burner on a shelf attached to the wall at some distance behind the motor, and to focus the light on the slit by means of a lens. No flicker could be seen in the spectrum except that due to the motion of the disc, which rotated in the path of the rays of light between the lens and the slit. As the disc had alternate sectors of 90 degrees cut out, the duration of a single flash of light was therefore one quarter of the time of a complete revolution. The general diagram of the apparatus is shown in figure 1. The speed of the motor was regulated by means of a simple form of brake (see fig-

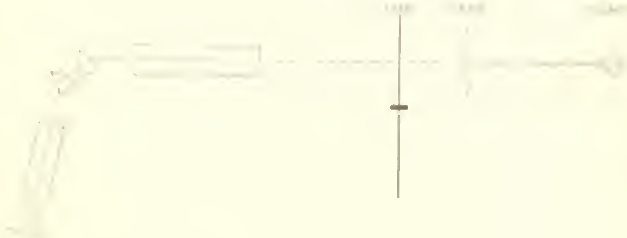

Fig. 1.

ure 2), made by passing a strip of leather over the smooth groove in the thumb screw that held the disc on the axle of the motor. One end of this leather was fastened to a spiral spring screwed to the table; the other had a long cord attached which was wound round a long brass rod turning in a friction socket, also screwed to the table. By turning this rod the string could be wound or unwound, and the friction of the leather on the axle of the motor increased or decreased. With this simple friction brake, the motor could be maintained constant at any speed from zero up to 1800 revolutions per minute for a period of several hundred revolutions.

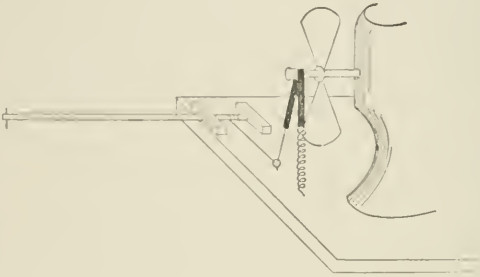

Fig. 2.

To record automatically the speed of the disc a small hand speed-counter was clamped in a position so that its rubber tip pressed firmly against the rear end of the axle of the motor (fig. 3). The rubber tip served to prevent the relative slipping of motor and speed-counter, and to insulate the latter, which was necessary as it carried a current. The small index on the counter was re-

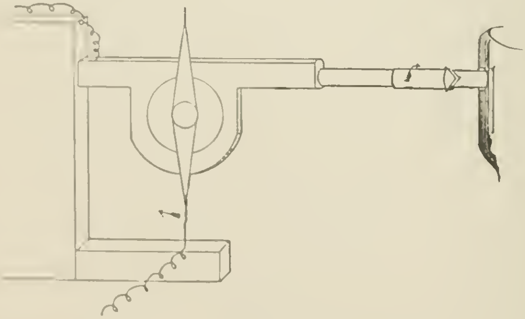

Fig. 3.

placed by a long diametral arm, the ends of which in turn closed the primary circuit of an induction coil at every fiftieth revolution of the motor. The secondary circuit of this coil passed through metal parts of a chronograph, with a narrow spark gap at the surface of the cylinder. At every fiftieth revolution of the disc, therefore, a spark perforated a piece of paper carried on the cylinder. The pendulum of a clock, by a mercury contact, closed the primary circuit of another coil every second, and similar perforations were made at these intervals on the same piece of paper. The time of fifty or one hundred revolutions of the disc could then be easily measured, and the duration of the flashes of light on the retina computed. In order to have the registering apparatus completely and conveniently under the control of the experimenter, the primary circuits of both coils ran to a double mercury key within easy reach. At the proper moment both circuits were closed simultaneously, and the clock and motor automatically made their records for whatever length of time was necessary.

The method of taking observations was as follows: By means of a diaphragm in the eye-piece of the spectrometer a narrow portion of the spectrum was isolated. The motor was then started at such a speed that the flickering of the narrow band became quite distinct. By relaxing the friction-brake, the speed was gradually increased until the flickering just disappeared and a uniform band of color was presented to the eye. The speed of the motor was then kept constant while the circuits were closed and the clock and speed-counter made their records. Generally the time sufficient for one hundred revolutions of the disc was recorded as being most convenient for purposes of computation. A little practice enabled one to complete a setting in half a minute. Where greater accuracy was required, the slight tiring effect was avoided by making the first adjustments with the left eye, after which the setting could be obtained by the right eye with an exposure of less than half the time mentioned. After each observation in the case of the normal curves, the eye was rested in diffused daylight for at least ten minutes. Two and sometimes more settings were made at each part of the spectrum; and so constant were the different adjustments of the apparatus, the intensity of the light, and the sensitiveness of the eye, that observations taken at different times, and even on different days, differed from the mean value by less than two per cent.

The room within which the apparatus was set up was dark, and all extraneous light was excluded; the only illumination being due to such light as escaped through the screens surrounding the acetylene flame.

To reduce the circle readings of the spectrometer and thus identify the parts of the spectrum in which observations were made, readings were made for various Fraunhofer lines and a calibration curve of the usual form was plotted.

In this investigation a large part of the work done was with the eye fatigued with variously colored light. In order to conveniently attain this object, a plan was adopted differing from that described by Burch in the paper already cited. In the dark room an arc light was placed on a stand in front of which hung a dark cloth curtain. Light passing through a hole in this was focused by a lens upon the slit of a large direct vision spectroscope, which also was calibrated, so that the wave length of the fatiguing light could be found. A diaphragm in the eyepiece cut off all the brilliant arc spectrum except a narrow band about two millimetres in width of the required color. The intensity of the light also rendered a very narrow slit possible, thus increasing the purity of the spectrum. The eye was fatigued by allowing a narrow band of any pure color from this spectrum to fall upon the center of the retina for at least five minutes, a length of time found sufficient to give the degree of fatigue desired. This accessory apparatus was so placed that when the eye had become fatigued the observer, by simply turning in his chair, could make the setting for the persistence, as described above, without any loss of time, and before the eye had any time to recover to any appreciable extent from the tiring process. In taking a series of observations this fatiguing operation was repeated before each setting, after the completion of which the recording apparatus required readjustment, which gave the eye one minute rest. No extended rest was considered necessary during the progress of a series of measurements, as Burch found that any fundamental color sensation could be exhausted without affecting the others. That this statement was abundantly justified will be seen upon a comparison of the normal persistency curves with those obtained for the eye when fatigued with various colors. The observations could therefore be taken with great rapidity.

When the eye was fatigued with any color, a piece of white paper placed where the white light from the arc fell upon it, appeared of a tint always complementary to the color affecting the eye. This afforded a convenient means of enabling the experimenter to determine the degree of exhaustion of the retina.

The time allowed for the fatiguing process with all colors was about five minutes. The uniformity of the measurements, for some of which this time was even doubled, seemed to indicate that with light of a given intensity the exhaustion of the color sensation reached a maximum in a few minutes, and that further exposure produced no effect. The following experiment served to confirm this inference: The eye was exposed to a band of pure red, the center of which had a wave length, $\lambda = .680\mu$, and persistence observations were made on a similar band of red the center of which had a wave length $\lambda = .758\mu$. Normal persistence = .0170 sec. The results are as follows:

Time of fatigue.	Persistence.
7 minutes.	.0195 sec.
5 "	.0193 "
10 "	.0188 "
20 "	.0188 "

Less than a minute rest was allowed between the readings except for the last which was made two days later. The eye accordingly was under a continued exhausting stimulus with the object of bringing about a greater degree of fatigue. The maximum exhaustion was apparently reached in seven minutes, though the other values may only differ by an experimental error. It may be, however, that the bright light tires the retina to a certain degree at first, after which the eye adjusts itself to the new conditions and partially recovers its normal condition. The above values would indicate this, though sufficient data are not yet available to establish this supposition. In any case the retina ultimately reaches a point of equilibrium between the destructive action of the external stimulus and the constructive power of the eye. If the luminosity of the source of light is increased, the degree of exhaustion will undoubtedly be greater, and the maximum may be reached in the same or even in less time.

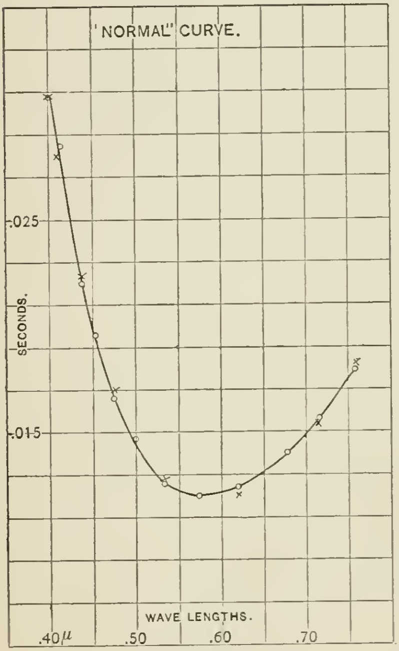

Fig. 4.

Normal Persistency Curves.

The first persistency curve obtained was the normal. As this was the standard with which curves for abnormal conditions of the eye were to be compared, the readings were taken with great care to avoid all sources of error. The eye was allowed to rest in diffused daylight for more than ten minutes before each reading. The values of this series of settings are given in Table I. They are also graphically shown in Fig. 4, in which ordinates represent the persistence of vision for various parts of the spectrum in seconds, and abscissæ are wave lengths.

To guard against error, observations with the eye in its normal condition were frequently made to see if any change had taken place. A series of such settings taken towards the latter part of the investigation is given in Table II. Their relation to corresponding readings upon the original normal curve is indicated by X's in Fig.

Table I.

Normal curve.

Wave length.	Persistence.	Wave length.	Persistence.
.400 μ	.0308 sec.	.533 μ	.0126 sec.
.415 "	.0285 "	.573 "	.0120 "
.438 "	.0220 "	.620 "	.0124 "
.454 "	.0196 "	.678 "	.0140 "
.475 "	.0166 "	.758 "	.0179 "
.500 "	.0147 "		

5. This curve, like the ones given by Nichols and by Ferry in the papers cited, shows that the persistence is least near the *D* line and increases towards both ends of the spectrum. The curves are parabolic in form.

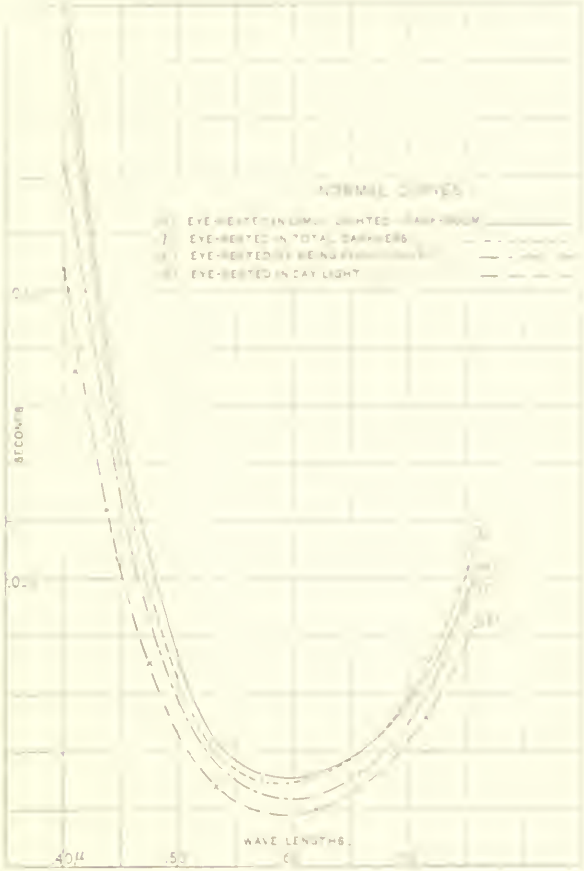

Fig. 5.

TABLE II.

Supplementary normal settings.

Wave length.	Persistence.	Wave length.	Persistence.
.400 μ	.0308 sec.	.533 μ	.0128 sec.
.410 "	.0272 "	.620 "	.0120 "
.438 "	.0224 "	.715 "	.0152 "
.475 "	.0171 "	.758 "	.0183 "

It was accidentally noticed at one time during a series of observations, that the duration of visual impressions was increased when the eye had been resting in the dark. This phenomenon was thereupon studied in some detail. Before each observation the eye was allowed to rest in the dark room in which the experiments were being conducted. This room was not completely dark, as the walls could be dimly seen, owing to the stray light from the acetylene flame. The results are given in column *a* of Table III. After coming out into the light, two of these readings were repeated and the following values obtained:

Table III.

Persistence after exposure to varying degrees of light and darkness compared with "normal" persistence.[1]

	Persistence under various Conditions.			
	a Eye rested in dark room.	*b* Eye rested in total darkness.	*c* Eye blindfolded.	*d*[2] Eye "normal" (exposed to diffuse day light).
.400 μ	.0398 △	.0390	.0344	.0308
.410 "	———	.0355	.0323	———
.415 "	———	———	———	.0285
.438 "	———	.0284	.0257	.0220
.454 "	.0246	———	———	.0196
.475 "	———	.0185	.0187	.0166
.500 "	.0172	———	———	.0147
.533 "	.0140	.0140	.0131	.0126
.573 "	.0132	.0130	———	.0120
.620 "	.0133	.0132	.0125	.0124
.678 "	.0145	.0148	———	.0140
.715 "	.0171	———	———	———
.758 "	.0200	.0211 ▽	.0199 ▽	.0179 ▽

Wave length.	Persistence.
.678 μ	.0132 sec.
.620 "	.0125 "

On comparing these with the values given in Table III (*a*) for the same wave lengths, the difference will be at once noticed.

It was thought that, as the walls of the dark room could be seen indistinctly, the eye was subject to a strain which might be really fatiguing it, and so increase the persistence of the color impressions. The observations were accordingly repeated, this time with the precaution of resting the eye in total darkness. The results are given in column *b* of Table III.

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[1] Arrows indicate the order in which settings were made.

[2] Repeated for convenience of comparison from table I.

These values are a little greater in the red than the corresponding ones in column *a*, but the two curves lie very close together, as will be seen by inspection of Fig. 5, in which these curves are compared. It is quite evident, therefore, that the increased sensitiveness of the retina in the dark increases the persistence of vision, which is just the opposite of the anticipated effect. The increase in the values of the persistence of different wave lengths is not uniform, being about 15 per cent. greater than the normal in the extreme red, 11 per cent. in the yellow, and 30 per cent. in the extreme violet. This result harmonizes with a statement of Parinaud,[1] who found that "the increase in the sensitiveness for light which is produced on a retina placed in the dark, is not equal for rays of different refrangibility." He further states that this is true for all parts of the retina except the yellow spot. As the observations described in this paper extended at the same time over the yellow spot and surrounding portions of the retina, it is not possible to state conclusively whether the above statement is confirmed or not. The persistence of vision being a function of the sensitiveness of the retina as well as of the intensity of the light stimulus, connects what is found in the curves just described with the observation of the French writer.

In these last experiments the eye was kept open while being rested, and it was decided to further test the supposition that the increased values of the duration of the impressions might be due to the strain of adaptation of the retina, or to some kind of muscular strain. For this purpose the right eye, the one used in all these experiments, was rested by being closed and blindfolded. All muscular strain at least was removed in this way, and the results, in column *c*, Table III, show that a different condition was induced in the eye.

These values, shown graphically with the others in Fig. 5, are intermediate between what may be termed the ordinary and extraordinary normal curves. In this comparison it will be seen that the hypothesis that the great increase in the duration of the color impressions is due to some kind of muscular strain is substantiated partially, since the elimination of that possible disturbing factor brought about a decrease in these values. There still remains a substantial increase which must be accounted for, the most obvious explanation being that it is due to the increased sensitiveness of the retina. This curve also shows that the increased sensitiveness of the retina is unequal for waves of different lengths, the increase above the normal being 9 per cent. in the red, 5 per cent. in the yellow and 12 per cent. in the violet. These results may be looked at from another point of view. According to the Hering theory, the sensation, or rather the lack of sensation, black, has the power of assimilation of the white-black visual substance. The eye in its normal condition is under the mild influence of daylight which would dissimilate this substance to a certain extent. Darkness, being the absence of any stimulus of the retina, permits the restoration of the white-black substance to its maximum sensitiveness. In case this is the explanation of the phenomenon, why should the restoration of this visual substance affect the various colors at all, and especially different colors in different degrees? Instead of the visual substances of the Hering theory being independent of each other, some connection must exist between them. Darkness cannot be held to assimilate simply the white-black substance, but also the red-green and yellow-blue. It would at least be supposed that if restoring the white-black substance did affect the others, that it would affect the red-green substance equally in both red and green, and similarly the yellow-blue substance. But the persistence of the red is increased 9 per cent., while the increase in the green is 13 per cent. The discrepancy is far greater in the other case, as the increase in the yellow is only 5 per cent., while in the blue it is 13 per cent. These facts can hardly be said to be in harmony with the theory in question. Similar objections can not be urged against the Young-Hemholtz theory, since it does not group the color sensations into pairs of opposites, nor does it limit the restoring power of perfect rest—darkness—to counteracting any specific stimulus of the retina.

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[1] M. H. Parinaud, De l'intensité lumineuse des couleurs spectrales. Comp. Rendus. Vol. 99, 1884, p. 937.

We have found so far that the persistence of vision is a maximum for all colors when the eye is rested by being kept open in total darkness. The values fall to an intermediate position when the eye is rested by being blindfolded, and reach a minimum when the rest has been given in diffused daylight. It would be expected that a considerable degree of exhaustion of the retina would have an opposite effect to that we have been discussing. But the experiments now to be described show that the opposite is the case—that fatiguing the retina causes the duration of the color impressions to increase again.

EFFECT OF FATIGUING THE RETINA WITH VARIOUS COLORS

Retina fatigued with red.

The eye was fatigued, as described in the first part of this paper, by looking at an isolated portion of a brilliant arc spectrum for about five minutes, the process being repeated before every observation. The condition of the retina with the red sensation partially exhausted, approximates that of the naturally red-blind person.

In this process a band of color about 2 mm. wide was used, the center of which in the case of red had a wave length $\lambda = .680\ \mu$.

The results of the measurements of the duration of the various color impressions upon the retina in this abnormal condition, are exhibited in Table IV, and graphically in Fig. 6, in comparison with the normal curve.

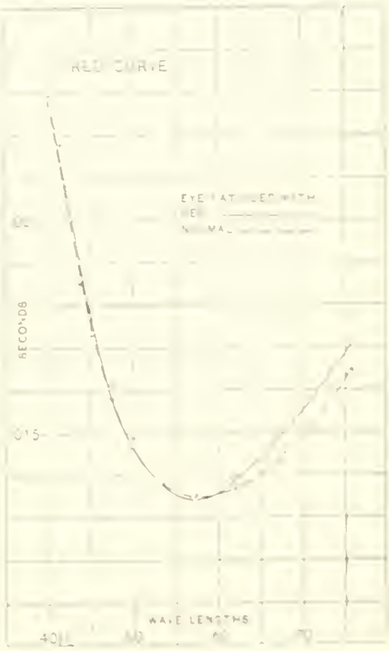

Fig. 6.

Comparing the two curves in Fig. 6, it is seen that fatiguing the eye with red has the effect of increasing the persistence of that color and also of about half of the orange, the remainder of the spectrum being unaffected in any way. The persistence of the red is increased by 8 per cent., while the increase in the same portion of the spectrum when the eye was blindfolded was 9 per cent., the two agreeing within the limits of experimental error. The Hering theory would certainly lead one to suppose that the green part of the curve would show some difference from the normal. A glance at the two curves, however, shows a perfect agreement between them. A similar lack of accordance of the experimental data with the anticipations of the Hering theory will be frequently noticed in the remainder of this paper.

Table IV.

Eye fatigued with red ($\lambda = .680\ \mu.$)

Wave length.	Persistence.	Wave length.	Persistence.
.400 μ	.0293 sec.	.533 μ.	.0126 sec.
.410 “	.0292 “	.573 “	.0118 “
.425 “	.0265 “	.620 “	.0128 “
.438 “	.0230 “	.657 “	.0137 “
.454 “	.0194 “	.678 “	.0150 “
.475 “	.0172 “	.758 “	.0192 “
.500 “	.0143 “		

It is to be noticed that the red sensation can be exhausted without affecting in any way the remaining sensations. This was a matter of some surprise; for upon looking at the acetylene spectrum after tiring the eye with red of the much more brilliant arc spectrum, all colors were apparently equally affected. The measurements showed that in this the eye was deceived. This confirms the statement of Burch in the paper previously cited, who, however, much more completely exhausted the color sensations than the author of this paper.

Retina fatigued with green.

The measurements in this case were made in the manner already described, but with the retina fatigued by a pure green light from the arc spectrum ($\lambda = .520\ \mu.$). The results are given in Table V, and graphically in Fig. 7.

This curve shows an elevation or bunch in the green indicating, as before, an increase of the persistence in that part of the spectrum,

TABLE V.

Eye fatigued with green (λ = .520 μ).

Wave length	Persistence	Wave length	Persistence
.400 μ	.0311 "	.512 μ	.0150 "
.415 "	.0253 "	.533 "	.0126 "
.435 "	.0206 "	.573 "	.0120 "
.460 "	.0157 "	.620 "	.0125 "
.475 "	.0170 "	.675 "	.0137 "
.492 "	.0164 "	.755 "	.0185 "

due to the tiring process. The maximum increase of the persistence of the green is about 12 per cent. which again coincides with the increase in the persistence of the same wave length when the eye was blindfolded. The curve coincides with the normal in the yellow and red, but runs under it in the blue and violet. The Hering theory would lead us to expect the curves to differ in the red; the Young-Helmholtz in both violet and red if they differed at all. For if one sensation were exhausted it is possible that the intensity of the remaining sensations might be increased, producing the effect noticed in the blue and violet, and a similar effect in the red. The same phenomenon will be noticed in two other curves (see Figs. 8 and 9), though since it is but slight it may be due entirely to experimental errors.

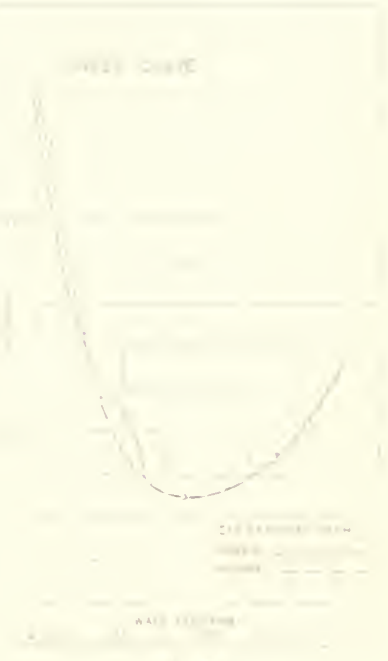

Fig. 7

Retina fatigued with violet.

The following values were obtained when the eye was fatigued with violet:

Table VI.

Eye fatigued with violet ($\lambda = .400\ \mu$).

Wave length.	Persistence.	Wave length.	Persistence.
.403 μ	.0350 sec.	.502 μ	.0122 sec.
.410 "	.0287 "	.533 "	.0110 "
.423 "	.0227 "	.596 "	.0109 "
.434 "	.0198 "	.657 "	.0125 "
.443 "	.0188 "	.715 "	.0149 "
.454 "	.0161 "	.758 "	.0176 "
.468 "	.0149 "		

The data are plotted in Fig. 8 in comparison with the normal curve. The only part of the curve affected is the violet, which shows results similar to those obtained in the two preceding curves. There is an almost complete coincidence of the curves from the blue to the middle of the red, the fatigue curve then falling a little below the normal. This illustrates the remarks made upon a similar ef-

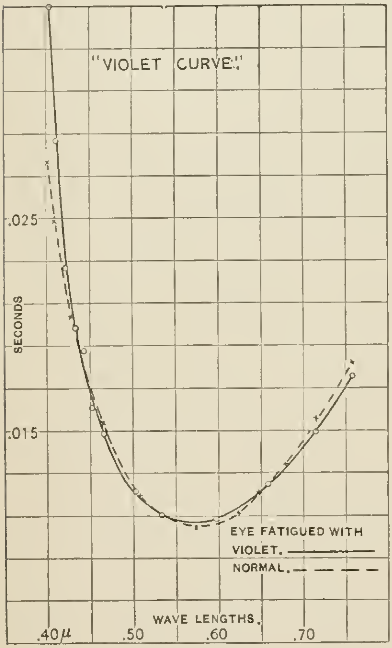

Fig. 8.

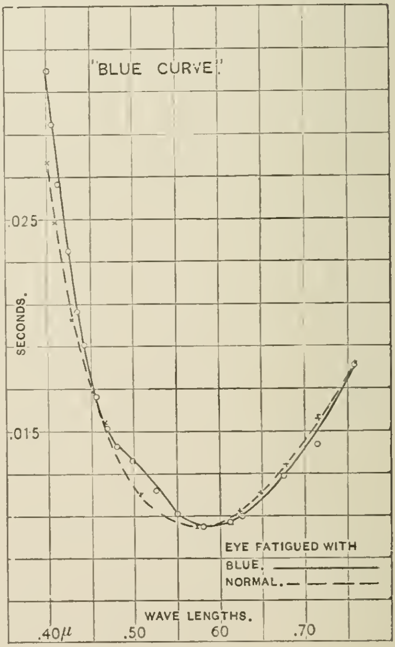

Fig. 9.

fect obtained in the abnormal curve for green. The persistence of the violet is increased by 27 per cent. These three curves for the eye tired with *red*, *green* and *violet* respectively, are of the same type, having one elevation which occurs in the part of the curve corresponding to the fatiguing color.

It would be quite natural to expect, in view of the results already discussed, that if blue and yellow are fundamental sensations in the same sense as are red and green according to either of the two most widely accepted color theories, similar elevations of the curve would be produced by using blue and yellow, respectively, as fatiguing stimuli, and these elevations would occur in the corresponding parts of the curves. In other words if blue and yellow are fundamental sensations, fatiguing the retina with these colors ought to affect these color sensations and no others. On the other hand, if blue and yellow are not fundamental, but compounded of two other sensations, then fatiguing with one of these ought not to show any effect in the part of the curve corresponding to that color, but should cause the elevations in the curve in the parts of the spectrum corresponding to those fundamental sensations which are affected. The latter is found to be the case.

Retina fatigued with blue.

Table VII shows the results obtained when the retina was exposed to blue light.

TABLE VII.

Retina fatigued with blue ($\lambda = .440\ \mu$).

Wave length.	Persistence.	Wave length.	Persistence
.400 μ	0320 sec	.498 μ	.0136 sec.
.405 "	.0295 "	.525 "	.0122 "
.414 "	.0267 "	.550 "	0111 "
.425 "	.0235 "	.580 "	.0105 "
.435 "	.0207 "	.612 "	.0107 "
.444 "	.0191 "	.625 "	.0110 "
.455 "	.0166 "	.675 "	.0129 "
.467 "	.0151 "	.715 "	.0143 "
.480 "	.0143 "	.758 "	.0182 "

These values will be found plotted in Fig. 9 in comparison with the normal curve. In the part corresponding to the blue, the two curves coincide, showing that in this region the persistence has not been changed by the fatiguing process. The persistence has however been increased in both the green and violet, which is shown by the elevation of those parts of the curve. In this case the increase in the green is 10 per cent. while for the eye fatigued with green it was 12 per cent. The increase in the violet is 16 per cent. against 27 per cent. for the case when the eye was fatigued with violet. The readings in the extreme violet were, however, subject to a greater experimental error, as the illumination of that part of the spectrum was comparatively feeble. The curve obtained for the eye exhausted with blue, is therefore practically the superposition of the green and violet curves. The deduction is obviously that the sensation of blue is the consequence of the excitation of the sensations of green and violet. It will be noticed that the blue curve runs under the normal in the red, a phenomenon observed in two previous curves. This is shown best in the violet curve, where the abnormal runs under the normal in both green and red, indicating that when the retina has been exposed to violet this sensation is exhausted, but the other fundamental sensations red and green, are rendered a little more acute.

Retina fatigued with yellow.

We have now to examine the results obtained when the fatiguing color was yellow. The arc spectrum was dispensed with in this case, and the arc was replaced by a sodium flame. The yellow sodium light was of sufficient intensity to fatigue the eye which was placed at the focus of a lens. The following results were obtained :

Table VIII.

Retina fatigued with yellow ($\lambda = .589\ \mu$).

Wave length.	Persistence.	Wave length.	Persistence.
.400 μ	.0312 sec.	.533 μ	.0143 sec.
.415 "	.0302 "	.573 "	.0124 "
.438 "	.0236 "	.620 "	.0124 "
.454 "	.0205 "	.647 "	.0128 "
.475 "	.0177 "	.678 "	.0140 "
.492 "	.0163 "	.715 "	.0164 "
.512 "	.0155 "	.758 "	.0201 "

This curve, plotted in Fig. 10, in comparison with the normal curve, shows the yellow, blue and violet regions to be unaffected, while elevations were produced in the green and red. The whole curve is a little above the normal, which is probably due to a slight change in the pressure of the gas making the spectrum a little less luminous. The maximum increase in the persistence of red impressions in this case is 10 per cent., while in the case of exposure to red it was 8 per cent. This may be compared also with the increase in the red when the eye was blindfolded, which amounted to 9 per cent. In the yellow curve the increase in the green is 12 per cent. which is exactly the same as in the green curve. The position of the maximum in the two cases is however not the same.

Yellow light, therefore, has the same effect on the retina as red and green together, and it must be concluded that the sensation of yellow is due to a simultaneous disturbance of the red and green visual apparatus. Whatever may be the "deliverances of consciousness" as to the purity of blue and yellow, in the light of experiment we are forced to conclude that they are not fundamental but compound sensations, as far at least as their effect on the retina is concerned. Further than that, this paper does not pretend to deal with them.

Retina fatigued with white light.

Having successively fatigued the retina with five well-defined spectral colors with the interesting results described, some curiosity was evinced as to the probable effect of tiring the retina with all wave lengths at once, that is with white light. From the standpoint of the Young-Helmholtz theory, it was thought that the curve in this case should show three elevations; in the red, the green and the violet. On the other hand, assuming the truth of the Hering theory, the white light would affect the white-black visual substance which is independent of the other two. Color sensations affecting the like-wise independent red-green and yellow-blue substances should accordingly show no change in persistence. The result does not confirm either expectation. To accomplish the fatiguing of the retina, the white light from the arc passed through a lens and fell upon a piece of white paper placed at a little distance from the focus. The round spot of light was partly transmitted and fell upon the retina for the usual time of five minutes. A series of after images followed which threatened to interfere with the accuracy of the observations. Upon looking at the portion of the spectrum in the field of view, it appeared as if seen through a hazy light of varying color. For the first few seconds this after image was of a faint yellowish tint which gradually deepened into an intense yellow completely obscuring the spectrum. The first hazy tint could be easily restored by winking, and this enabled the observer to take the readings always under the same conditions. The results given in Table IX, are so uniform as to inspire belief in their accuracy.

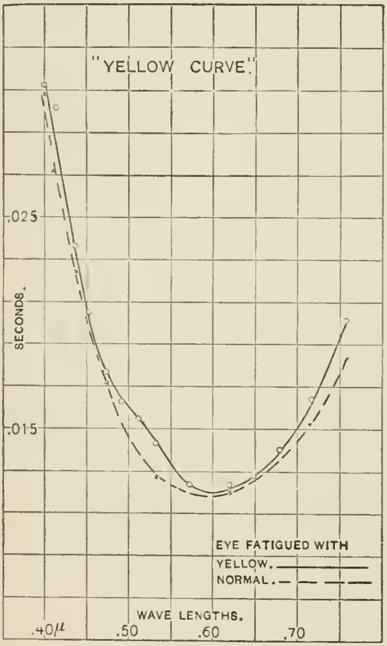

Fig. 10.

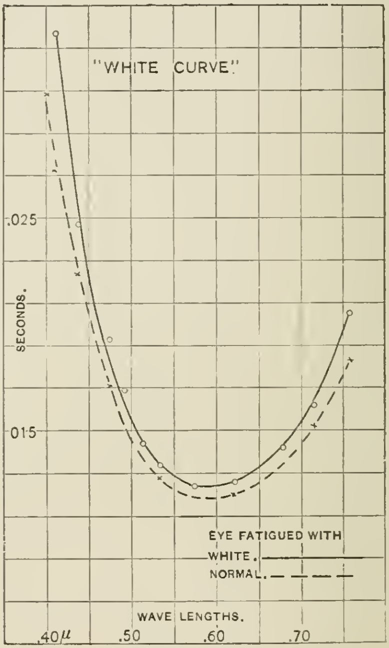

Fig. 11.

These data are plotted in figure 11 in comparison with the normal curve. The curves, it will be noticed, are approximately parallel, indicating no elevations in any part. Apparently this does not confirm the Young-Helmholtz theory of the sensation of white. The fact that the persistence of all the color sensations is increased shows an interdependence of the visual substances not provided for by the

Hering theory. But at any rate the curve seems to indicate the existence of a white sensation partially connected with and partially distinct from the fundamental color sensations. That white is either an independent or semi-independent sensation, is claimed by Ebbinghaus and by Mrs. Franklin in their theories, and Abney[1] has recently obtained experimental results which point to the same conclusion.

TABLE IX

Eye fatigued with white light.

Wave length.	Persistence.	Wave length.	Persistence
.410 μ	.0337 sec.	.573 μ	.0124 sec.
.438 "	.0247 "	.620 "	.0126 "
.475 "	.0193 "	.678 "	.0142 "
.492 "	.0169 "	.715 "	.0161 "
.512 "	.0144 "	.758 "	.0205 "
.533 "	.0134 "		

In the discussion of the various curves thus far considered (Figures 4 to 10), the *percentage increase* of the duration of color impressions has been given. For greater convenience of comparison these values have been brought together in the following table:

TABLE X.

Percentage increase in the duration of color impressions when the eye is fatigued by exposure to various colors.

Region affected.	Color of the fatigue stimulus.						
	Red.	Green.	Violet.	Blue.	Yellow.	White.	Eye blindfolded.
Red.	8 %	0 %	0 %	0 %	10 %	9 %	12 %
Yellow.	0	0	0	0	0	5	5
Green.	0	12	0	10	12	13	7
Blue.	0	0	0	0	0	13	10
Violet.	0	0	27	16	0	12	14

When it is remembered that the values in this table represent experimental results obtained at intervals during several months, that no attempt whatever was made to keep the eye in a condition of constant sensitiveness, and that the conditions under which the abnormal states of the retina were induced varied to a considerable extent from time to time, the results, especially in the red and green, show a uniformity that may very properly be considered remarkable. It can be no mere chance agreement of results. Certainly the retina, even under abnormal conditions, cannot have such a varying sensitiveness as is generally supposed. The values do not differ, for each color, by more than the presumable experimental error, except one value in the green and one in the violet, which will be evident on referring to the table. The averages of the tabulated results are as follows :

---

[1] Abney, Sensitiveness of the Retina to Light and Color. Phil. Trans., A., 1897. Vol. 190.

Red,	9.75	per cent.
Yellow,	5	"
Green,	10.8	"
Blue,	11.5	"
Violet,	17.2	"

In all these experiments the retina has apparently been brought to a maximum abnormal condition, though the fatiguing light has been of varying intensity. There are not sufficient experimental data yet to show whether greatly increasing the intensity of the light exhausting the retina, will increase this maximum condition or not, though it is anticipated that it will.

It has already been pointed out that, when the retina is made abnormally sensitive by being kept in the dark, the persistences of the various color sensations are unequally increased. The same is true when the retina is fatigued ; for when any colors have their persistences affected, the increase is unequal in different parts of the spectrum, in all cases being least in the yellow and reaching maxima in the red and violet.

BEARING OF THE FOREGOING RESULTS UPON EXISTING THEORIES OF COLOR SENSATION.

The Hering Theory.

According to this theory, as is well known, the color sensations are arranged in three pairs, red-green, yellow-blue, and white-black. Since the first sensation in each pair is produced by the dissimilation of a supposed photo-chemical substance, which exists in three forms to correspond to the three pairs of color processes, it would be expected that all being affected in precisely similar ways would show similar results. One would also expect the assimilating colors to show opposite effects. Whatever effect is produced by fatiguing the retina with red, an exactly similar effect should be shown with the yellow. So also for green and blue. Reference to the curves shows that red has an elevation in the red, while yellow gives two, neither of which corresponds to that color, and white gives none, or rather the whole curve is elevated above the normal. Similarly for the others—green, has one, blue two, and black none, if we may consider the curve obtained by blindfolding the eye as the one corresponding to black. We thus have three types of curves for the three pairs of color sensations. The agreement in number is the chief point of harmony with the Hering theory.

Analyzing the curves more particularly, we may observe, first, that acting on the red-green substance with red light has dissimilated it, producing a characteristic result. Assimilating this same substance with green light produces a similar result but in the part of the curve corresponding to green. Certainly the theory would expect each operation to affect both red and green parts of the curve, or else each would affect one and the same part but in different ways. Violet, too, giving a result similar in every way to those produced by red and green, must be placed on an equal footing with them, and whether it be considered as a dissimilation or an assimilation color its opposite must be found in the spectrum. Exhausting the retina with yellow discloses no special substance that is acted upon, but elevations are produced in both red and green. Translating this into the language of the theory, yellow simultaneously exercises the functions of both red and green to the same percentage amount, as we have seen, as each of them separately. Under these circumstances a balance should have been maintained between the opposing actions of red and green, which should have produced a curve differing in no respect from the normal. Supposing however that the action of the yellow stimulus is in harmony with the requirements of the theory, exposure of the retina to its assimilative companion blue ought to counteract the effects previously produced. Experiment shows that the green is affected, but in addition the violet is also affected which was not disturbed at all by the yellow. Further, by stimulating the retina with strong yellow and blue lights alternately, the red-green substance could be overbalanced, and red-blindness induced by the action of certain luminous waves which according to theory should have no effect in this direction. It is quite evident, therefore, that these experimental results are antagonistic to the theory in question. The curves obtained when the eye was rested in the dark and fatigued with white light at first sight seem to confirm the Hering theory; but since in both cases all the color sensations are affected, there must be an intimate connection between white, black, and the color processes. This, too, is not in harmony with the provisions of the Hering theory.

The Ebbinghaus Theory.

The same objections will also apply to the theory of Ebbinghaus,[1] which is practically a modification of that of Hering. The main difference is that while the latter postulates three visual substances which may be regarded as so many independent variables, the former separates these substances into four for the perception of color and one for white, making in all five independent variables. The fundamental color tones in this theory are the same as in that of Hering, viz., red, yellow, green and blue, two of which, yellow and blue, have been shown to be compound.

The Franklin Theory.

The ingenious color theory of Mrs. Franklin[2] is framed partly from the physical and partly from the psychological standpoint. This evolutionary theory regards color-sense as a development out of an earlier existing gray-white sensation. Guided only by the requirements of consciousness the fundamental color tones would be red, green, yellow and blue. But physical experiments have rendered it improbable that yellow is fundamental, so the theory is resolved into a three-color one, with a gray-white sensation in addition. Consciousness must be satisfied with only a part of its demands.

---

[1] Ebbinghaus, Theorie des Farbensehens. Zeitschrift für Psychol. und Phys. der Sinnesorgane, Bd. V., Heft 3, 1893.

[2] C. L. Franklin, On Theories of Light-Sensation, Mind, Vol. 2, N. S. No. 8, 1893.

The experiments described in this paper are equally fatal to both blue and yellow as fundamental sensations, but can be considered hostile to this theory only as regards the blue. Mrs. Franklin might then go one step farther and assume the Young-Helmholtz color-sensations by the substitution of violet for blue.

The Young-Helmholtz Theory.

The experiments we have described are plainly seen to harmonize completely with the fundamental color processes of the Young-Helmholtz Theory. Red, green and violet being these fundamental sen-

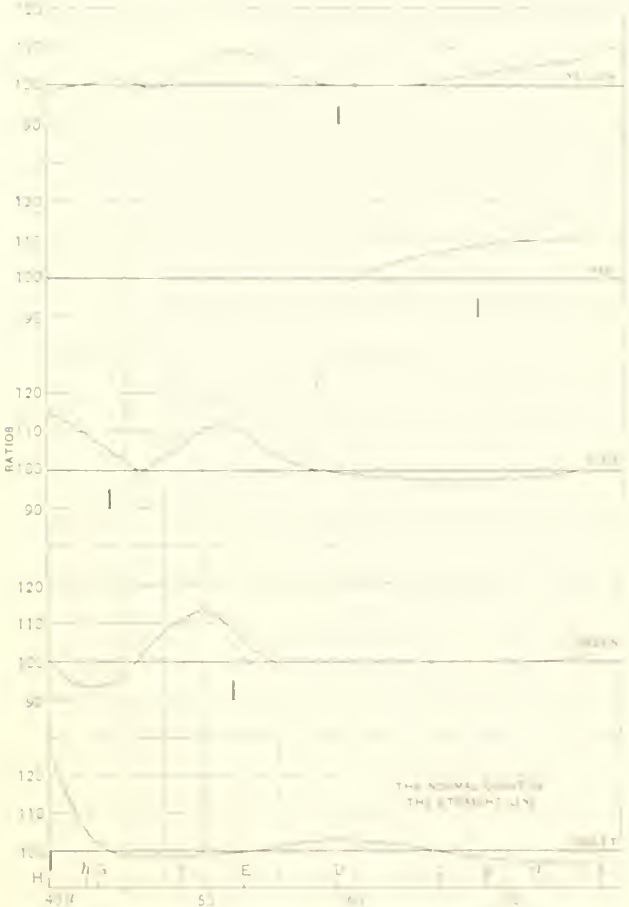

Fig. 12.

sations give characteristic results in an abnormal condition. Yellow and blue are both compounded of two other sensations, and experiment shows the theory verified. Rest in the dark makes all sensations more sensitive, which is shown by the curve obtained under this condition. The curve obtained for the action of white light, however, cannot be disposed of so easily, and, as before, we must consider it as evidence in support of a white sensation. There are many other color theories; but these we have considered may be considered typical of all.

At the suggestion of Dr. Nichols these curves have been drawn in another way which shows the deviations of the abnormal from the normal curves in a much more striking manner. All parts of the normal curve are reduced to the same ordinate, making that curve a straight line parallel to the axis of abscissæ. The corresponding values of the abnormal curves are then reduced in the same ratio and these ratios plotted. For convenience the ordinate of the normal curve is taken as 100. The variations from the normal, discussed in the preceding pages, are much more evident especially in the parts corresponding to the blue and violet regions of the spectrum. It is evident that this is a representation of what would

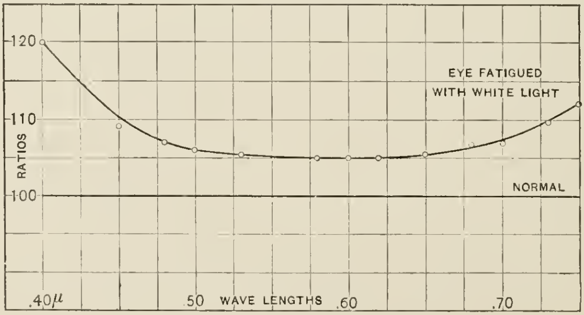

Fig. 13.

actually have been obtained, had all parts of the spectrum possessed the same luminosity.

Only those curves obtained when the eye was fatigued with various colors and with white light are so reduced, as the others do not show their characteristics any better by this method. The five color curves are plotted together for comparison in Fig. 12, the white in Fig. 13. In addition the same curves are plotted in Fig. 14, with circle readings as abscissæ instead of wave lengths, which

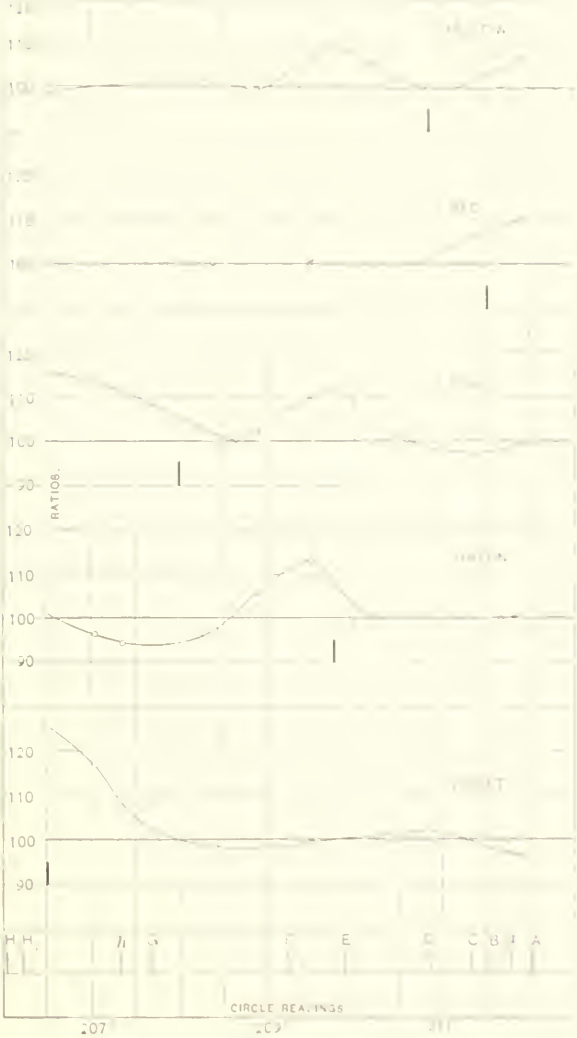

Fig. 14

represents the conditions of experiment more accurately, as the observations were made on a prismatic spectrum.

In these last diagrams the part of the spectrum used for fatiguing the eye is marked by means of a vertical line under the respective curves.

Examinations of Naturally Color-Blind Persons.

S. W. F., a student in Cornell University who was known to be color-blind, kindly consented to allow his eyes to be tested. Being accustomed to make scientific measurements, his observations were made with care and accuracy. The limits of the spectrum were the same to him as to the normal eye. The apparatus did not permit his neutral point to be determined accurately, but he indicated it to be at about $\lambda = .480\ \mu$. As is usual with red-blind persons, he called all on the red side of the neutral point yellow, and the other blue. When tested with the Holmgren worsteds he made the usual matches of the red-blind. In addition, however, he indicated blindness of some other part of the retina, as shown by his matches of light yellows and greens. Measurements were made *for both eyes* in the manner described for obtaining normal curves.

The following table gives the persistence of color impressions for the right eye:

Table XI.

S. W. F. (right eye).

Wave length.	Persistence.	Wave length.	Persistence.
.410 μ	.0297 sec.	.533 μ	.0133 sec.
.438 "	.0246 "	.550 "	.0128 "
.455 "	.0214 "	.573 "	.0133 "
.465 "	.0202 "	.596 "	.0124 "
.475 "	.0184 "	.620 "	.0128 "
.484 "	.0170 "	.678 "	.0161 "
.493 "	.0162 "	.715 "	.0191 "
.512 "	.0148 "	.758 "	.0224 "

The data are plotted in Fig. 15 in comparison with the third normal curve of the writer. These values show a very great increase in the duration of the impressions in the red; the curve then approaches nearly to the normal in the yellow, then rises in the yellowish-green forming a curious little bunch or elevation, thence continuing parallel to the normal through the blue and violet. It will be noticed that the whole curve is displaced upward, which indicates that the whole spectrum was not as bright to the color-blind eye as to the normal. This bunch in the yellow-green is not accidental nor is it due to an erroneous measurement, since it was confirmed by experiments several weeks apart. It is also confirmed in the curve for the left eye of the same subject, shown in figure 16 in comparison with a new normal curve of the writer, the determination of which was rendered necessary by a change in the pressure of the acetylene and consequently a change in the luminosity of the spectrum.

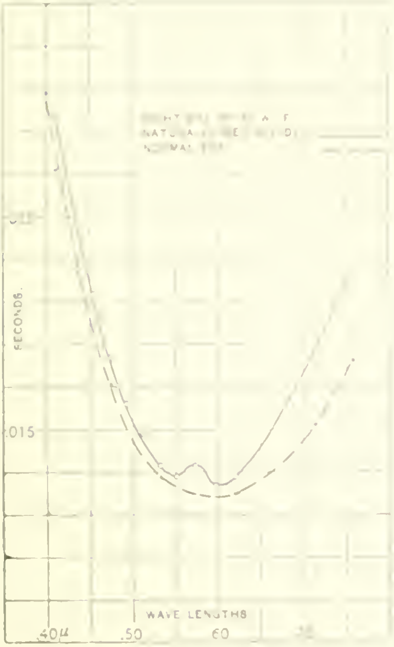

Fig. 15.

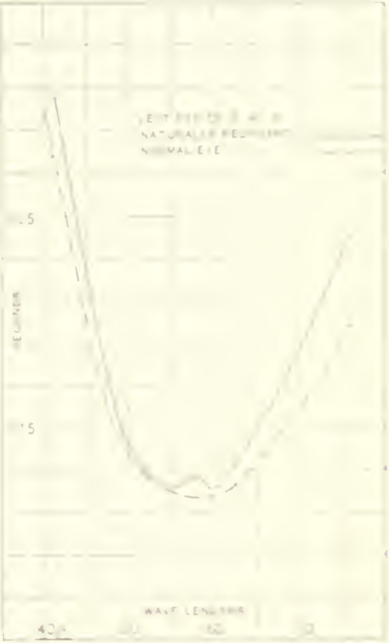

Fig. 16.

The form of the curves is the same for both eyes, both showing the same peculiarities. It may be possible that this is the curve of the typical red-blind subject. Ferry, however, in the article cited, found curves slightly different from these for red-blind persons. In his curves there were no elevations in the yellow-green part of the spectrum. The curve for the normal eye (Fig. 6), fatigued with red, shows the increased persistence of the red though not to the same extent as the naturally color-blind subject. No disturbance of the curve occurs in any other part.

Table XII gives the data for the left eye.

Table XII.

S. W. F. (left eye).

Wave length.	Persistence.	Wave length.	Persistence.
.410 μ	.0307 sec.	.550 μ	.0122 sec.
.455 "	.0216 "	.573 "	.0127 "
.465 "	.0201 "	.596 "	.0121 "
.475 "	.0176 "	.620 "	.0135 "
.484 "	.0162 "	.678 "	.0170 "
.493 "	.0146 "	.758 "	.0240 "
.533 "	.0125 "		

Mr. J. E. T., of the Chemistry department of the University, informed the writer that he had some difficulty in observing red lines in spectroscopic analysis, and kindly consented to make the necessary observations for his persistency curve. When tested with the Holmgren worsteds he matched the proper colors with the confusion samples, and seemed as far as that is concerned to have normal color vision. But finally being tested with other samples he made matches which indicated a partial red-blindness at least, and also a disturbance of the violet. He stated also that some difficulty was experienced with violet lines in spectroscopic work.

The values of the persistence are given in the following table:

Table XIII.

J. E. T.

Wave length.	Persistence.	Wave length.	Persistence.
.400 μ	.0428 sec.	.574 μ	.0112 sec.
.415 "	.0296 "	.596 "	.0114 "
.438 "	.0214 "	.620 "	.0119 ".
.475 "	.0157 "	.678 "	.0144 "
.500 "	.0136 "	.715 "	.0184 "
.533 "	.0117 "	.758 "	.0224 "
.550 "	.0114 "		

These values, for the right eye, will be found in Fig. 17 in comparison with a normal curve of the writer. Both eyes, the right and left, gave approximately the same curve, only one of which is here plotted. It will be noticed that the part of the curve corresponding to red shows a characteristic elevation above the normal, indicating red-blindness. Through the yellow-green the points on the curve were obtained quite close together to see if any elevation occurred as in the previous case. No deviation from a smooth curve was, however, obtained. The persistence of green is shown to be, in this case, less than in the normal eye, indicating that, to the former, green was relatively much brighter. This is quite in agreement with other cases of color-blindness studied by various observers. Comparison of the two curves also shows that the lowest point on

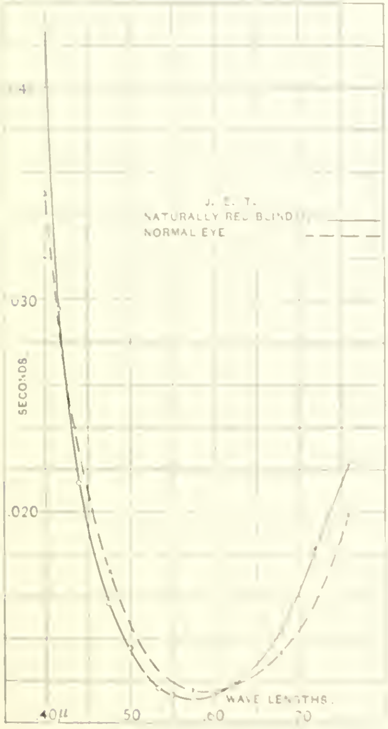

Fig. 17.

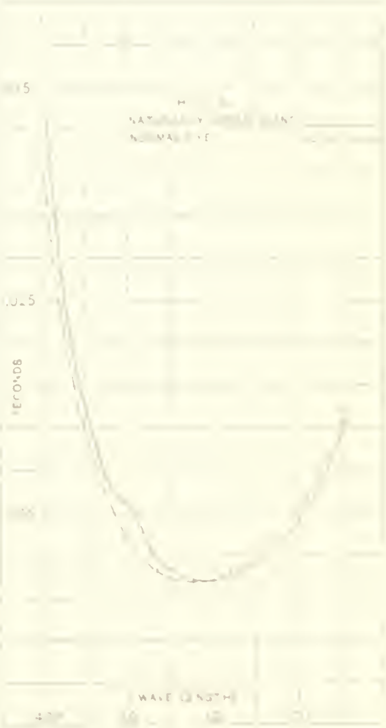

Fig. 18.

that obtained for the color-blind eye does not correspond to the same part of the spectrum as the similar point on the normal, but is displaced towards the blue end of the spectrum. This indicates that the point of maximum brilliancy is shifted in that direction, a result also commonly observed. The curve also shows a persistence greater than normal in the extreme violet. Though there is greater difficulty in making observations in this region than in any other, yet since all Mr. T's readings here were greater than for the normal eye, it must indicate some abnormal condition of the retina as regards its appreciation of violet. It is not possible to say conclusively, without further investigation, whether this is a case of violet color blindness or not.

Another student of the University, Mr. H. C. B., also consented to determine his persistency curve. Upon examination with the worsteds he indicated green-blindness. Persistency curves for both eyes were obtained, but their close agreement renders only one necessary. The following values for the left eye were obtained :

Table XIV.

H. C. B. (left eye).

Wave length.	Persistence.	Wave length.	Persistence.
.405 μ	.0336 sec.	.538 μ	.0127 sec.
.454 "	.0201 "	.574 "	.0119 "
.487 "	.0160 "	.620 "	.0120 "
.502 "	.0152 "	.678 "	.0135 "
.517 "	.0139 "	.758 "	.0194 "

These values will be found plotted in Fig. 18 in comparison with a curve for the normal eye. The characteristic elevation in the green is well shown, though the persistence is not increased to quite the extent anticipated. It may indicate only a partial green-blindness. No other part of the curve differs from the normal. This curve, and the one preceding, show that an eye may be color-blind to red or green without necessarily affecting any other sensation, a conclusion which does not agree with the Hering theory of color blindness.

From these three curves for color blindness, it is not possible to draw many definite conclusions ; but there is evidently reason to believe that the study of many cases of color blindness by this method will throw a new light upon this interesting subject, and may lead to important evidence as to the real nature of color-vision itself. Preparations for such an investigation, on the part of the writer, are being made.

SUMMARY.

The results arrived at in this investigation may be conveniently summed up as follows :

1. The persistence of all color impressions reaches a maximum when the eye has been kept open in the dark, the increased duration being unequal for rays of different refrangibilities. The increase is least in the yellow, and grows larger towards both the red and violet. The curve obtained under such conditions may be called the *extraordinary* normal curve.

2. The persistence of all color impressions is a minimum when the eye is under the influence of diffused daylight. The curve thus obtained has been termed in this paper the *ordinary* normal curve.

3. When the eye has been blindfolded the values of the persistence in all cases are intermediate between the extraordinary and ordinary normal curves, showing, however, unequal increases as in the extraordinary curve.

4. When the retina has been exposed to strong red, green or violet light, the persistence of impressions of the same color as the fatiguing light is increased, forming a characteristic elevation or bunch in the part of the persistency curve corresponding to that color.

5. When the retina has been fatigued with yellow or blue light there is no increase in the persistence of impressions of those colors, but the characteristic elevations are produced in the parts of the curves corresponding to red and green or green and violet respectively.

6. These phenomena strongly confirm the fundamental color sensations of the Young-Helmholtz theory.

7. When the retina has been fatigued with white light, the persistences of all color impressions are unequally increased. This apparently does not harmonize with the Young-Helmholtz theory, but indicates a partially independent white sensation.

8. Both rest and fatigue of the retina cause an increase in the

persistence of all colors. No explanation of this fact has yet been found.

9. In the case of naturally color-blind eyes, the persistence of color impressions to which the retina is blind is abnormally increased, thus affording a method of determining the wave lengths to which the retina is incapable of responding normally.

10. In addition to the loss of one fundamental color sense, the naturally color-blind retina may also lack the power of responding to a group of waves affecting another sensation. The further study of cases of color blindness in this way would probably throw new light upon this interesting and important subject.

In conclusion, I wish to gratefully acknowledge my indebtedness to Professor E. L. Nichols, who suggested the subject and method, and also to Mr. J. S. Shearer, of the department of Physics, for their many valuable suggestions regarding both apparatus and the experimental results of the entire investigation.

Physical Laboratory,
Cornell University, May, 1900.

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THE HYPOTHESIS OF COLOR VISION

By Frank Allen

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THE HYPOTHESES OF COLOR VISION.[1]

By Frank Allen

TO the question "How do we see?" there are but two general replies, the eye must emit something, or something from without must enter the eye. For twenty centuries this was a debated question among philosophers who took sides with the leaders of their respective schools, and vigorously upheld their theories. A complete absence of experiment in this as in other branches of science was accompanied by an astonishingly great variety of arguments and extravagant hypotheses to support their adopted opinions. Colors were ranked among the bodies of which only the names were known. When philosophers were asked, for example, why such a body was red, they answered that it was in virtue of a quality which made it appear red.

It is far from obvious that white light is very complex in its nature; and failure to discover this resulted in the confusion of mind exhibited by writers on light and colors preceding Newton's decisive experiments.

In the following short sketch of the history of this interesting branch of science an attempt is made to outline briefly most of the hypotheses of both ancient and modern writers. An outline only is attempted because a full review would expand this paper into a volume.

For the present purposes the history of color vision is here divided into four periods: first, from Pythagoras to Newton (540 B. C.–1671 A. D.); second, from Newton to Thomas Young (1671–1801); third, from Young to Ewald Hering (1801–1874); fourth, from this last date to the present time.

First Period (540 B. C.–1671 A. D.).

Pythagoras and the Pythagoreans, the second school of Grecian philosophers, who flourished about 500 B. C. held the opinion that

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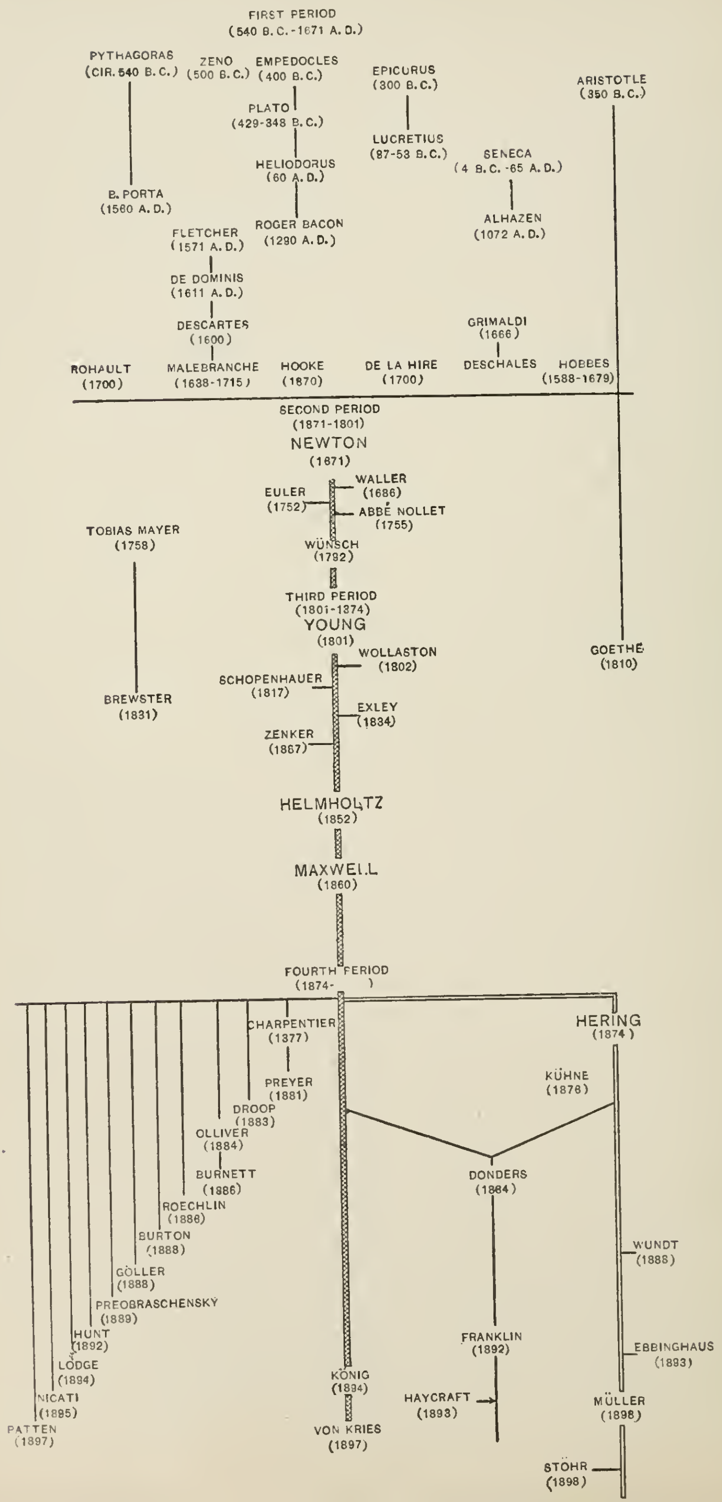
[1] A Report made to the Physical Seminary, Cornell University, 1902.

HYPOTHESES OF COLOR VISION



vision is caused by particles continually flying from the surfaces of bodies and entering the eye.

A century after these, Empedocles and Plato maintained the doctrine that the cause of vision is something emitted by the eye which meeting with something else that proceeds from the object is thereby reflected back again. In other words sight was considered a species of touch due to invisible feelers having their origin in the eye.

Aristotle (De Anima, Lib. 2, Cap. 6; 350 B. C.) maintained that light is incorporeal. His ideas are best illustrated by a reference to the rainbow, in accounting for which very many theories of color production originated. He thought that the colors were due to imperfect reflection from raindrops, the image of the sun being distorted and color only exhibited. Aristotle also taught that black and white were the colors from which all others were derived, an idea which in modified form persisted to the time of Goethe. It was also supposed by some philosophers of this period that the rainbow was caused by the clouds communicating their color to the sunbeams.

Epicurus (300 B. C.) and after him Lucretius (75 B. C.) believed that we see by the intervention of light as we feel an object by means of a stick. Seneca, who flourished about 60 A. D., observed (Nat. Quest., Lib. 1, Cap. 7) that sunlight shining through an angular piece of glass gives the colors of the rainbow, which he explained as a species of false color such as is observed on the neck of a pigeon. His theory of the rainbow is interesting. "The rainbow must be circular of necessity just as waves spread in a circular manner from a disturbance in still water." Again, he says "that the rainbow is the image of the sun reflected from a hollow moist cloud which distorts the image because of the nature and figure of the speculum. Since in water everything is seen larger, the image of the sun is large because it is reflected from a moist cloud which partakes of the nature both of glass and of water." The different colors are accounted for by supposing that they come partly from the sun, partly from the clouds, and form a mixture?

Heliodorus, a Stoic philosopher of Nero's time, adhered to the old theory of the emission of ocular beams, which he tried to strengthen by arguing from the shape of the eye.

Ptolemy, whose treatise on optics written about 150 A. D. is now lost, became the great authority on the subject to the time of Alhazen.

During the Dark Ages the Arabians were the scientific investigators. The treatises of two of them, Al Farabi and Ebu Haithem (about 1000 A. D.), are not now extant; but that of Alhazen, published about 1072, became the authority for the five succeeding centuries. His speculations on color do not however show any advance over those of European philosophers. He defines the colors of the rainbow to be three, but with Seneca supposes them to be produced by a mixture of sun's light with the blackness of the cloud from which it is reflected. In the same manner the colors of all bodies seen by reflection are tinged with the colors of the reflecting surface (Optica, p. 461). The colors due to refraction in a glass globe, he says, are not the same as those of the rainbow, because they are not of the same number and are not seen in the same way — by reflection — but by direct vision in the same manner as light itself.

Roger Bacon, who died in 1294 A. D., assented to the opinion of some of the ancients and of some of his contemporaries as well, that visual rays proceed from the eye. His great reason was that everything in nature is qualified to discharge its proper functions by its own powers in the same manner as the sun and other celestial bodies. He regarded the presence of light necessary for vision (Opus Majus, p. 289).

Johannes Baptista Porta, who published his work, "Magia Naturalis," in 1560 when but fifteen years old, performed experiments with the camera obscura, invented by himself at that time, which convinced him that vision was caused by the intromission of light into the eye. Light was considered by him to be colorless but capable of having color superinduced upon it from foreign causes. He also gives an account of the generation of each color of the rainbow from a mixture of light and the denser or rarer parts of the air. Later Porta expressed the opinion that the colors of the rainbow were produced by refraction in the whole body of rain or vapor and not in the separate drops (De refractione, p. 95).

Fletcher, of Breslau (1571), tried to account for the colors of the rainbow by means of two refractions in one drop and a reflection from a second, but as is well known, Antonio De Dominis, Bishop of Spalatro (1611) arrived at the true explanation (De radiis visus et lucis).

To account for the color he supposed that the red rays were those that had traversed the least space inside the drop and accordingly retained most of their native force, and striking the eye more vigorously gave it a stronger sensation. Similarly green and blue were produced by those rays, the force of which had been in some measure lessened in passing through a greater body of water. All the intermediate colors were composed of mixtures of these three primaries according to the hypothesis which generally prevailed at the time.

The theory of De Dominis was adopted and mathematically investigated by Descartes (1596–1650). But while sound in his investigations of the paths of the rays, he was much less happy in the way he accounted for the production of colors. "Light is neither a substance nor yet a mere property of bodies, but the motion of a subtle fluid communicated by the pressure of a luminous body. It is affected by two motions, a circular and a direct. When the circular is quicker than the direct the color is red; if the direct is quicker the color is blue; when the motions are equal the color is yellow. All the other colors are composed of these primaries." Descartes was, however, the first to state the real nature of black and white.

Malebranche (1638–1715) modified this theory of Descartes by the substitution of a medium filled with fluid vortices instead of perfectly elastic solid globules.

Following the example of other philosophers, Thomas Hobbes (1588–1679), an English writer, published a theory based upon experiments with a prism. The colored rays he considered to be due to modified light which he divided into two parts and named "first" and "second" light. The following extracts (English Works, vol. 1, p. 450; Molesworth Edition) will give an idea of his hypothesis. "Colour is light, but troubled light, namely such as is generated by perturbed motion as shall be made manifest by the red, yellow, blue and purple which are generated by the interposition of a diaphanous prism." "It is therefore evident that when weak but first light passeth through a more resisting diaphanous body as glass, the beams which fall upon it transversely make redness: when the same first light is stronger the transparent beams make yellowness. When the second light is strong green is produced, but when weaker it generates purple.

"Whiteness is light, but light perturbed by the reflections of many beams of light coming to the eye together within a little space. Blackness is the privation of light."

Hobbes also considered that colors are formed from a mixture of white and black.

Perhaps the most extravagant opinion ever formed upon the subject of color vision was that of Dr. Hooke the contemporary and rival of Newton. Hooke reduced the primary colors from three to two. "Blue is an impression on the retina of an oblique and confused pulse of light whose weaker part precedes and whose stronger part follows; and red is a similar impression whose stronger part precedes and whose weaker follows. The fantasm of colour is caused by the sensation of the oblique or uneven pulse of light which is capable of no more varieties than two, which arise from the two sides of the oblique pulse though they be capable of infinite gradations, each of them beginning from white and ending, one of them in the deepest scarlet and the other in the deepest blue." (Priestley "On Vision, Light and Colours.")

De la Hire, who lived at this time, supposed difference in color to depend upon the degree with which the same light affects the optic nerve. For example, red blood appears blue through the veins because the light in passing through the skin loses its power and affects the nerve with less force. In common with many other writers he assigned the blue color of the sky to the sunlight reflected by the air, seen against a background of dark space.

Grimaldi (De lumine, coloribus et iride, 1666) made the discovery that when a circular beam of light passes through a prism it forms an oblong image. He did not infer the different refrangibilities of the colored rays, but looked upon it as showing that refraction produced color as well as reflection, which was the more general way according to the philosophers. Grimaldi's idea of color was that it was condensed light, red being more condensed than blue.

He concluded with Aristotle that light is no real substance, not a substantial but an accidental quality.

Priestley (On Vision, Light and Colours, p. 249) thus sums up the theories of color production to the time of Newton.

"The Pythagoreans called colour the superficies of a body. Plato said that it was a flame issuing from them. According to Zeno it is the first configuration of matter, and Aristotle said it was that which moved bodies actually transparent. Descartes very sensibly argued that colour is a modification of light; but he supposed that the difference of colour arises from the prevalence of the direct or rotatory motion of the particles of which it consists. Father Grimaldi, Deschales, and many others thought the differences of colour depended upon the condensation and rarefaction of light. Malebranche was of the opinion that differences in colour depend upon the quick or slow vibrations of a certain elastic medium filling the whole universe. Rohault imagined that the different colours were made by the rays of light entering the eye at different angles with respect to the optic axis; and from the phenomena of the rainbow he pretended to calculate the precise angle that constituted each particular colour. Lastly Dr. Hooke, the rival of Newton, imagined that colour is caused by the sensation of the oblique or uneven pulse of light; and this being capable of no more than two varieties, he concluded that there could be no more than two primary colours."

Note.— Most of the hypotheses comprising the First Period will be found in Priestley's "On Vision, Light and Colours."

SECOND PERIOD (1671–1802).

1671. Newton. "New Theory of Light and Colours." Philo. Trans. (abridgment), Vol. I., p. 678. Reprinted in Pop. Sci. Monthly, Sept., 1902.

Newton performed his experiments on the decomposition of white light in 1666, but apparently did not publish the results until several years later. The following quotations from several of his papers will give his general views on color vision.

"The rays of light to speak properly are not coloured. In them is nothing else than a certain power and disposition to stir up a sensation of this or that colour."

"To the same degree of refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of refrangibility."

"To explain colours I suppose that * * * the rays of light by impinging on the stiff refracting superficies, excite vibrations in the ether * * * of various bigness; the biggest, strongest or most potent rays, the largest vibrations; and others shorter according to their bigness, strength or power; and therefore the ends of the capillimenta of the optic nerve, which pave or face the retina, being such refracting superficies, when the rays impinge upon them, they must there excite these vibrations which * * * will run along the aqueous pores or crystalline pith of the capillimenta through the optic nerve into the sensorium; and there, I suppose, affect the sense with various colours according to their bigness and mixture; the biggest with the strongest colours, reds and yellows, the least with the weakest, blues and violets; the middle with green; and a confusion of all with white * * *."

1686. Waller: Phil. Trans., vol. 3, p. 274.

In this paper Waller describes the materials from which pigments of definite colors are made. He also briefly mentions experiments in which he mixed the simple red and yellow pigments with each of the simple blues, and concludes that these mixtures of primaries give most of the medium colors, namely, green, purple, etc.

1752. Euler: Nova theoria lucis et colorum. Lettres à une Princesse d'Allemagne, 1768. · Nos. 23, 27 and 28.

Euler upheld the undulatory theory and strongly opposed the doctrine of light corpuscles. But he maintained that bodies became visible because the sun's rays fell upon them, throwing their particles into motion, generating in their turn rays which, affecting our eyes, rendered the bodies visible. The blue color of the sky he explained by supposing the dust suspended in the atmosphere to generate blue rays owing to their constituent particles being thrown into vibration by the sun's light.

1755. Abbé Nollet: Leçons de Physique, Tom. 5, Sec. 3. Quoted by J. D. Forbes: Phil. Mag., S. 3, Vol. 34, p. 172, 1849.

This writer taught the Newtonian theory of light and colors, but maintained the primary qualities of orange, green and purple.

1758. Tobias Mayer: Gottingsche gelehrte Anzeigen, p. 147. Quoted by Helmholtz, Phil. Mag., S. 4, Vol. 4, p. 533, 1852.

The three colors, red, yellow and blue had been mixed as pigments in early times, and came to be regarded somewhat as primary colors. "Mayer was the first to give utterance to the view that the three primitive colours might correspond to three different kinds of light, red, yellow and blue, each of which furnished rays of all refrangibilities. According to this, at every point in the solar spectrum, red, yellow and blue rays are mixed together which do not differ in refrangibility and therefore cannot be separated by the prism."

1792. Chretien Ernest Wunsch: Versuche und Beobachtungen über die Farben des Lichtes. Leipsic. Abstracted in Annals de Chimie, 64, p. 135, 1807.

Wunsch performed many experiments to prove that there were not seven primary colors as some supposed from the number of spectrum colors given by Newton, nor yet five as others believed. He was the first to select red, green and violet as primaries, a result to which he was led by his experiments on mixtures of the colored rays of the spectrum.

Third Period (1801–1874).

1801. Thomas Young: "On Theory of Light and Colours." Phil. Trans., Vol. 92, p. 12, 1802 (read in 1801). "Some Cases of the Productions of Colours." Ibid., p. 387.

In the first paper Young selected red, yellow and blue as the three simple color sensations, with no other basis than current scientific opinion. Owing to the celebrated but misconstrued observations by Wollaston of the dark lines in the solar spectrum, Young modified his theory by selecting red, green and violet as primaries, quite independently, however, of Wunsch. This theory he further confirmed by experiments, after which it remained in obscurity until Maxwell and Hemholtz brought it to the attention of scientists and made it the basis of their investigations.

Young seems to have been the first to attribute a definite physiological significance to the three primary colors, the precise hues or wave-lengths of which he had no means of determining. His general principles were modified and made definite by the experimental researches of Helmholtz, Maxwell, König and others. These do not all agree upon the hues selected as the primary colors, and Maxwell in particular selects a blue as the third of his triad of fundamentals.

"The referring of all colours," says Helmholtz, "to the three primitive ones has, in the case of the different observers, three different senses:

"1. That the different colours were such as permitted of the formation of all others from their combinations.

"2. Or, as supposed by Mayer and Brewster, that the primitive colours correspond to three different kinds of objective light.

"3. Or, as supposed by Young, that they correspond to three primitive modes of sensation experienced by the visual nerves, and from which the remaining sensations of colour are composed."

[Helmholtz: "On the Theory of Compound Colours." Phil. Mag., S. 4, Vol. 4, 1852, p. 522. Also "Physiol. Optik."]

[Maxwell: "On Theory of Compound Colours, and the Relations of the Colours of the Spectrum." Phil. Trans., p. 57, 1860.] See also A. M. Mayer: "History of Young's Discovery of his Theory of Colors." Amer. Jour. of Science, Ser. 3, Vol. 9, p. 251, 1875.

1802. William Hyde Wollaston: "A method of examining refractive and dispersive powers by prismatic reflection." Phil. Trans., Vol. 92, p. 378.

In this paper Wollaston records his discovery of the principal "Fraunhofer" lines, the nature of which he was far from suspecting. He supposed that they divided the spectrum into four parts and formed the boundaries of the four corresponding colors, red, yellowish-green, blue and violet, the color of each division being quite uniform. He says that "we may distinguish, upon the whole, six species of rays into which a sunbeam is divisible by refraction." These are the four visible ones mentioned and in addition the invisible ultra-violet and infra-red. Wollaston evidently considered his four colors to be simple objective colored light.

This paper was important since it led Young to revise his theory.

1810. Goethe: "Farbenlehre." English translation "Theory of Colours." Eastlake.

The hypothesis of Goethe is merely the absurd doctrine of the ancients that color is a mixture of light and darkness developed to a very high degree. "Light and darkness," Goethe says in the introduction to his work, "or light and its absence are necessary to the production of color." He bases his views on observations made by looking at a broad field of light (e. g., a window) through a prism, and draws the general conclusion that next to the light a color appears which is called yellow; another appears next to the darkness which we call blue. When these are mixed in equal proportions the resulting color is green. All these colors produce new tints by being mixed with darkness.

Goethe's writings on color are remarkable for the abuse and denunciaton which he heaped upon the experiments and color theory of Newton. To some of the propositions of Newton he applied such terms as "incredibly impudent," "mere twaddle," "ludicrous explanation," and others of a similar character.

1816. Schopenhauer: "Ueber das Sehen und die Farben." Abstract in Encyc. Brit., Vol. 21, p. 450.

"The distinction of white and black with their mean point in the gray is referred to the activity or inactivity of the total retina in the graduated presence or absence of full light. The eye is endowed with polarity by which its activity is divided into two parts qualitatively distinct. It is this circumstance that gives rise to phenomena of colour. All colours are complementary. Each pair makes up the whole activity of the retina and so is equivalent to white; and the two particular activities are so connected that when the first is exhausted the other spontaneously succeeds. Such pairs are infinite in number. But there are three pairs which stand out prominently and admit of easy expression for the ratio in which each contributes to the total action. Red and green (each equal to 1:1); orange and blue (2 : 1); yellow and violet (3 : 1)."

1831. Brewster: On a New Analysis of Solar Light. Trans. Roy. Soc. Edin., Vol. 12, p. 123, 1834. (Read in 1831.)

Awarded the Keith Biennial Prize in 1834 by Roy. Soc. of Edin.

The theory of Brewster is an elaboration of that of Mayer based on observations of an *impure* spectrum. The main points of the theory are as follows:

1. Red, yellow and blue light exist at every point of the solar spectrum.

2. As certain proportions of red, yellow and blue lights constitute white, the color of every point of the spectrum may be considered as consisting of the predominating color at any point mixed with white light.

3. By absorbing the excess of any color at any point, white light appears at that point which cannot be decomposed by any number of refractions.

The great reputation of Brewster induced most physicists for more than twenty years to adopt this view, Airy, Melloni, Draper, and Helmholtz alone dissenting. This theory persists to the present time, and as Rood remarks, is almost universally believed by artists.

Helmholtz investigated the experiments which misled Brewster, and showed that he had employed a spectrum mixed with stray white light.

1834. Thomas Exley. "Physical Optics," p. 28.

The following condensed extract will give a general idea of the views of this writer:

"The atoms of light have equal velocities, but unequal momenta and spheres of repulsion; hence they ought to produce different effects or sensations on the delicate organ of vision. Probably those ethereal atoms which penetrate deepest into the sensitive part of the eye to produce their greatest effect give the red color, and those which pierce to the least depth produce violet, and those intermediate in proportion. Therefore the atoms which have the greatest absolute force and the least sphere of repulsion will cause a red color, and others according to one or other or to the proportion of both these circumstances will produce the same or other colors."

1867. W. Zenker. "Versuch einer Theorie der Farben perception." Archiv für Mikroskopische Anatomie (Schultze), Bd. 3, p. 248.

The retinal layer from which the rods and cones project acts as light reflector, according to the author. The layer of rods and cones is supposed to have a greater refractive index than the layer above. Part of the light entering the eye is absorbed, and part reflected, the latter being the portion of the radiant energy which excites the sensation of color. The elements of the retina may be considered as systems of surfaces upon which the incident light-waves fall perpendicularly, and from which they are reflected in the same manner. These result in systems of standing waves and nodes at fixed distances from the reflecting layer, the distances depending upon the wave-lengths. The point of maximum disturbance will therefore be different for waves of different refrangibilities. The rods and cones, he says, are like piles of plates, each plate having a thickness equal to three standing waves of red, four of blue, and five of violet. The loops of the standing red waves will therefore always affect different plates from those acted upon by blue and violet, and hence these sensations will always be excited by the proper wave-lengths. This theory accordingly makes color perception a function of space not of time.

FOURTH PERIOD (1874–).

1874. Ewald Hering. A series of six papers in . Sitzungs. der Kaiserl. Akad. der Wissen. zu Wien. (Math.-Naturwiss Classe). Fifth paper : Grundzüge einer Theorie des Lichtsinnes. 69 (3), p. 179, 1874. Sixth paper : 70 (3), p. 169.

Papers collected under the title : Zur Lehre vom Licht-sinnes. Vienna, 1878.

The hypothesis of Hering, the great rival of the Young-Helmholtz theory, is based upon the idea of visual substances. Hering assumes six psychophysical processes corresponding to six primary sensations which may be arranged in complementary pairs, black-white, blue-yellow, green-red. Three photochemical substances are supposed to exist in the retina, one corresponding to each of the pairs of sensations. The sensations of white, yellow and red are caused by the dissimilation of the corresponding visual substances, and the sensations of black, blue and green are caused by the assimilation of the same substances. These substances are not present in equal amounts. All the rays of the visible spectrum have a dissimilating action on the black-white substance, but different rays in different degrees. Mixed light appears colorless when it acts on the blue-yellow or red-green substance with equal dissimilative and assimilative power. The effects are not complementary merely but antagonistic. For example, fundamental red and green do not produce white by their combination, but merely destroy each other's effect and leave visible the white which is already there. This is not strictly true of the white-black antagonism, for their actions do not destroy each other but give rise to a series of grays. Each visual sensation is really a mixture of all six fundamental sensations. The one of the six which has relatively the greatest weight gives the character and name to the mixed sensation.

1876. Kühne. Papers in : "Verhandlungen des Naturhistorische-Medicinischen Vereins zu Heidelberg," 1877–79.

Following close upon the discovery (1876) by Boll of the "Visual purple," Kühne constructed a theory of vision. He supposes that the waves of light give rise in the retina to different compounds according to their length, and thus produce the different color sensations.

1877. Augustin Charpentier. "De la vision avec les diverses parties de la rétine." Archives de Physiol., 4, p. 894; also, "Sur la distinction entre les sensations luminenses et les sensations chromatiques," Compt. Rend., 86, 1878, pp. 1272 and 1341. Theory further developed in numerous other short papers in Compt. Rend., *e. g.*, 2 Semes, 1885, p. 275. Also see Nineteenth Century, August, 1893, Vol. 34, p. 258 in art. "Recent Science" by Kropotkin.

This theory distinguishes in optical phenomena : first, a luminous sensation ; second, a chromatic sensation ; third, a visual sensation, or a sensation of form. Charpentier supposes a double process—chemical and thermal—of colored light upon two different pigments of the retina. The photochemical effect of light decomposes the visual purple and generates in the optic nerve one sort of vibrations totally independent of the color, and varying in amplitude with the intensity. Another pigment is supposed to be located between the rods and the cones which absorbs light and heat. This absorption generates in the nerve another set of thermal or thermo-electric undulations which always begin a little later than the former, the interval being greater for violet than for red.

Two waves are thus moving along the optic nerve with corresponding phases at different intervals. Their various combinations provoke a variety of sensations which we interpret as so many colors.

1881. W. Preyer: "Ueber den Farben und Temperatursinn mit besonderer Rücksicht auf Farbenblindheit." Pflüger's Archiv, Bd. 25, p. 31.

In every color sensation Preyer distinguishes three parts: quantity or intensity; quality or tone; temperature. The intensity depends upon the force with which the retina is acted upon by the ether waves, the quality upon their amplitude. He also makes an æsthetic division of colors into two classes, warm and cold. The warm colors are from red to yellow green, the cold from this latter to violet. The color process is developed from an earlier existing temperature sense, and indeed the color sense may be considered a special case of the thermal sense limited to the retina. In this hypothesis, each retinal nerve fiber sensitive to color impressions terminates in two "cones," one of which is excited by warm colors and the other by cold, the deciding factor being the wave length. The rods give sensations only of white, gray, and black, the cones the color sensations.

1882. E. Landolt: "Théorie de la perception des couleurs." Arch. d'Ophthalm., II., p. 70.

1883. H. R. Droop: "Colour Sensations." Phil. Mag., S. 5, 15, p. 373.

This very indefinite theory of color vision is based upon two cases of color blindness described by Holmgren. One of the persons saw only red and bluish green in the spectrum and was blind to blue and yellow; the other saw yellow and blue, but was blind to red and green. As these were cases of monocular color blindness their observations were accurately described. From these data he outlines a theory comprising five fundamental sensations, the complementary pairs red-green, yellow-blue, and the sensation of white. No suggestion is given as to what are the retinal processes by which the colors are perceived.

1884. A. Angelucci: "Una nuova teoria sulla visione," communic. preventiva presentata All' Acad. Med. de Roma, 14 July, 1884. Also in: Rec. d'Ophthalm., p. 34, 1886.

1884. F. C. Donders: "Noch einmal die Farbensysteme," Graefe's Archiv für Ophthalmologie, Bd. 30 (1), p. 15.

The theory of Donders comprises features of both the Young-Helmholtz and Hering theories, and at the same time introduces some new ideas of the possible mechanism of color perception; the most prominent being that of successive partial dissociation of the complex color molecules of a single visual substance, which gives rise to the four simple color sensations, red, yellow, green and blue. It is thus a four-color theory, but he supplemented this by a three color theory (red, green, violet) under certain conditions in order to obtain for his theory the advantages which a three-color theory has.

1884. C. A. Olliver. "A Correlation Theory of Colour Perception." Phila. Med. Times, 14, p. 715, 1883–4.

"Each and every healthy optic-nerve filament transmits to the color-center of the brain for recognition, nerve energies equal to as many special sensations as its peripheral tip is capable of perceiving. Color perception takes place through each and every optic nerve filament." Instead of separate nerves for several independent fundamental color sensations with the retina as the distinguishing factor, the "color-center" of the brain perceives color according to the specific energy transmitted.

1886. Roechlin.

The theory of this writer is that yellow and blue are the only two simple colors of the spectrum, the third being always found fused with yellow or blue to form reds and violets. Roechlin asserts that purple may be produced by combining violet and yellow, as well as by the mixture of red and blue.

1886. S. W. Burnett. "The new Theory of Color-perception." Amer. Jour. Ophthal., Vol. 3, p. 278.

In this theory the brain is made the differentiating organ, and the nerve fiber is supposed to undergo different changes according to the different colors striking the retina. The same nerve is the conducting apparatus for different colors, which set up corresponding undulations, and these are the sources of different color sensations.

1888. W. Wundt. "Die Empfindungen des Lichtes und der Farben." Philos. Studien, 4, p. 311.

Apart from every external light stimulation and from all equivalent internal stimuli such as pressure, the retina is in a constant condition of internal stimulation. To this corresponds the sensation black, which also in part accompanies the light stimuli giving rise to the sensation gray.

By means of every external retinal stimulation two different excitation processes are set free — a chromatic and an achromatic — which follow different laws. With weak stimulation the achromatic has the greater intensity, with moderate light excitation the chromatic is more intense, while with the most intensive stimulation the achromatic is again predominant. The achromatic excitation consists in a *uniform* photochemical process which reaches its maximum in the yellow. The chromatic consists in a *polyform* photochemical process which represents a periodic function of the wave-length. Antagonistic action occurs not between the color stimuli themselves, but between the photochemical processes, and results in leaving a colorless light stimulus.

1888. Chas. V. Burton. "Experiments on Colour-perception, and on a Photo-Voltaic Theory of Vision." Cambridge Philos. Proc., Vol. 6, 1886–9, p. 308.

The author bases his theory upon experiments of Dewar and McKendrick (Edin. Philo. Trans., XXVII., 141), who have shown that there is a considerable electromotive force between the anterior portions of the eye and a transverse section of the optic nerve. It was found that the current flowing was altered in amount materially when light fell upon the retina. Yellow and green rays produced the greatest effect. The converse phenomenon is well known that an electric current applied to the optic nerve produces a sensation of light.

The theory suggested is that electric currents in the nerve fibers produce the sensation of light, and, if of sufficient intensity, of color also. The light of all wave-lengths falling upon the retina affects these currents in various degrees, which produce the phenomena of color. Persistence of vision is explained by a reverse current due to a polarizing electromotive force.

1888. A. Göller. "Die Analyse der Lichtwellen durch das Auge." Dubois-Reymond's Archiv für Physiologie, I. and II., p. 139. Reviewed by C. L. Franklin : Am. Jour. Psych., Vol. 2, 1888–9, p. 155.

Göller explains the analysis by the eye of light waves into sensations of differently colored lights by rotatory polarization. "Monochromatic light, on entering the eye, passes through the transparent retina, and is reflected back from the pigment epithelium in a state of plane polarization. The outer members of the cones play the part of a plate of quartz — they shift the plane of polarization by a definite angle. A molecular motion of much slower period is then set up in the protoplasm of the inner members, and it is the sensitiveness of the nervous filament to the plane of this motion which constitutes the sensation of color. Two complementary colors are colors which have had their planes of polarization rotated, one ninety degrees more than the other, with a phase difference of a quarter wave-length, the amplitudes being the same. These conditions would be sufficient to cause their superimposed harmonic motions to produce the motion of circular polarization, and that would be indistinguishable from the motion produced by all the colors of white light acting together.

Two vibrations whose planes are at different angles would give an elliptic motion of such a kind that the direction of its major axis would give its tint, the excess of the major axis over the minor would give its saturation, and the minor axis would give the amount of white light mixed with it."

1889. Preobraschensky. "Hypothese des Farbensehens." Jour. Russ. Phys.-chem., phys. part. 21, p. 248. Abstract : Jour. de Phys., II., 9, 1890, p. 538.

In this article the author very seriously modifies the Young-Helmholtz theory. In place of three kinds of nerve elements he supposes two — one sensitive to waves from .400 μ to .600, the other to those between the wave-lengths .520 and .790. The simple sensations correspond to the extreme vibrations. The gray sensation is produced by the simultaneous impression of the same intensity of two colors equally distant from the extremes. The perception of the intensity of light is the same in both theories.

1892. C. L. Franklin. "Eine neue Theorie der Lichtempfindungen." Zeit. für Psych. und Physiol. der Sinnesorgane, 4, p. 211.

"On Theories of Light-Sensation." Mind, N. S., 2, 1893, p. 473.

"In the earliest stage of its development the visual sense consisted only in the sensation of gray, *i. e.*, the whole black-gray-white series of sensations. There is a certain kind of molecule, called the 'gray-molecule' which is composed of an outer range of atoms somewhat loosely attached to a firmer inner core, and having different periods of vibration. The light waves of the entire spectrum in some measure, and particularly those of the middle part, have the power of tearing off this outer sheath of atoms which react chemically upon the retinal nerve ends, and bring about the sensation of gray. The color molecules are developed from the gray molecules in the following manner: The atoms of the outer range segregate themselves into three different groups at right angles to each other, and having three different average velocities. Light of the fundamental color tones (red, green and blue) tears off from a large number of molecules those atom groups whose periods are synchronous with the vibrations of the light, and those special chemical substances are set free which excite the respective color sensations. Intermediate waves set free atoms of two kinds and so give rise to mixtures of colors. Certain mixtures of light set free all three kinds of nerve-exciting substance which results in the gray sensation."

1892. Edmund Hunt: "Color Vision." Glasgow.

In a critical essay Hunt discusses several of the existing theories of color vision, and the interpretations of their experiments made by various writers. In addition he presents a theory of his own. Rejecting the various three-color and four-color theories, he maintains that there are five pure or principal colors: red, yellow, green, blue and purple. No attempt is made to describe any retinal processes by which the pure colors and their mixtures are perceived. Black and white are not considered as sensations.

1893. J. B. Haycraft: "A new Hypothesis concerning Vision." Proc. Roy Soc., 54, p. 272, 1893.

This paper briefly outlines an evolutionary theory in which color perception is a development of an earlier existing light-sense. To be concrete, the sensation of yellow has in the course of evolution been produced by pigments which stimulate the eye by the yellow, red and green spectral rays which they transmit. The red and green rays when mixed do not, however, give rise to red and green sensations, but simply intensify the yellow sensations. In a similar way combinations of other rays are treated.

1893. H. Ebbinghaus: "Theorie des Farbensehens." Zeit. für Psych. u. Physiol. der Sinnes., 5, p. 145. Reviewed by C. L. Franklin. Mind, N. S., 3, p. 198, 1894.

This theory is a development of Hering's, with the distinctive idea—partial dissociation—of Donders. "The visual purple is identical with a photochemical substance of such a nature that its primary partial dissociation is the cause of the sensation of yellow, and its completed dissociation is the cause of the blue sensation. In the cones which contain no visual purple, that substance does in reality exist, but is concealed by the presence of a second visual substance which is successively green, red and white in color (*i. e.*, is always complementary in objective color to the visual purple in all its color changes) and which is the source of our sensations of red and green. There is a third colorless substance in rods and cones alike whose decomposition is the source of the normal white-gray sensations, and of the sensations of the totally color-blind as well as of those of the normal eye when temporarily color-blind owing to insufficient illumination, besides contributing to the brightness of all sensations of light."

1894. Oliver J. Lodge. "The Work of Hertz." Nature, Vol. 50, p. 137.

In this review of Hertz's work a brief outline of an electrical theory of vision is given as follows: "I therefore wish to guess that some part of the retina is an electrical organ, say like that of some fishes, maintaining an electromotive force which is prevented from stimulating the nerves solely by an intervening layer of badly conducting material, or of conducting material with gaps in it; but that when light falls upon the retina these gaps become more or less conducting and the nerves are stimulated. This intervening layer acts as a coherer affected by Hertzian waves, or as selenium affected by ordinary light. The sensation of light is due to electrical stimulus; the sensation of black is due to the mechanical or tapping-back stimulus. Vision is persistent until the latter stimulus occurs. The energy of vision is supplied by the organism; the light only pulls a trigger."

1894. A. Konig. "Ueber den menschlichen Sehpurpur und seine Bedeutung fur das Sehen." Sitz. Akad. Wiss. Berlin, Vol. II., p. 577.

In his papers Konig has developed the Young-Helmholtz theory along the line of assigning specific functions to the rods, cones and visual purple. "He believes that the cones have nothing to do directly with the luminous sensation, but that they are catoptric instruments for the purpose of condensing light upon the walls of the pigment epithelium, where the photochemical processes take place which are the sources of the sensations of red, yellow and green. The blue sensation is furnished exclusively by the visual yellow of the rods, and the sensation of a faint light (and that of the totally color-blind) is also blue in quality and is due to the visual purple. Hence the fovea, where there is no visual purple, is blind to blue. The blue blindness of the fovea has not been confirmed by other observers."

1895. W. Nicati. "Theorie de la couleur." Archiv. d'Ophtal., XL., p. 1. Reviewed by C. L. Franklin, Psychol. Rev., Vol. 3, 1896.

The author uses such words as protochroism, metachroism, pleochroism, for gray vision, partial color-blindness and normal vision respectively. There is no difference in rods and cones that will cause three-color sensations, but in the "bipolar cells" there is a separation of the terminations into three layers for the three sensations. The visual purple is chemically affected by light and generates electric currents which are conducted by threads of varying resistances. The strength of current which is conveyed by each thread determines the character of the color sensation. Suitable cells are provided near the threads which send down condenser discharges to undo the effects of the first currents. For example, after red has been seen the discharge causes green.

1896. G. E. Müller. "Der psychophysischen Axiome und ihre Anwendung auf die Gesichtsempfindungen." Zeit. für Psychol. u. Physiol. des Sinnes., Bd. 10, 1896, p. 1. Second paper; *ibid.*, p. 321. Also two other papers, Bd. 14, 1897. Reviewed by C. L. Franklin: "Professor Müller's Theory of the Light Sense." Psychol. Rev., Vol. 6, 1899, p. 70.

The theory set forth in these lengthy papers is a modification of Hering's. Instead of the dissimilation and assimilation of visual substances as provided by Hering, Müller takes advantage of a conception of modern chemistry, namely the reversibility of chemical action under suitable conditions, which conditions, he assumes, are realized in the retinæ of vertebrate animals. The chemical law of mass action is also used in treating of the intensity of the photochemical processes. The pairs of sensations are the same as in Hering's theory except that a slight difference is made in the white-black process. Müller makes use of the "self light" of the retina in modifying the antagonism which exists between the black and white sensations. These do not naturally counteract each other perfectly, and so Müller assumes that the "self light" produces the gray effects. No use is made of the visual purple as a substance for producing vision, but it is regarded as an aid in bringing about adaptation to faint light.

1897. J. von Kries. "Ueber Farbensysteme." Zeitschrift f. Psych., XIII., p. 241. "Krit. Bemerk. zur Farbentheorie," *ibid.*, XIX., p. 175. 1898.

Von Kries in what has been termed a "reconstruction" of the Young-Helmholtz theory apparently inclines to the view "that there are two sorts of white — one physiological and brought about by a photochemical dissociation in the rods; the other psychical and due to a mental reconstitution of an even red-green-blue sensation into a sensation of indistinguishable quality from the first." In the latter case the red, green and blue sensations are occasioned by disturbances of the cones alone.

1897. W. Patten. "A Basis for a Theory of Color Vision." Amer. Naturalist, 32, p. 833. Abstract: Science, N. S., 7, 1898, p. 210.

"The theory is based on the structure of retinal cells in invertebrates. The structures in the eyes of invertebrates corresponding to the rods and cones of vertebrates are generally composed of groups of simple or compound wedges, containing systems of transverse fibrils accurately graded in length, according to their position in the wedges. The fibrils are always arranged in planes at right angles to the rays of light. All the fibrils in these planes may be parallel to one another, or at varying angles, or they may radiate from the axis of each rod like the bristles on a test-tube cleaner, so that no two fibrils in the same plane are parallel. By assuming that the length and angular relations of a fibril determine the amount of its response to a wave of light of a given length and plane of vibration, it is possible to offer a logical explanation of many phenomena of color vision."

1898. Adolph Stohr. "Zur Hypothese der Sehstoffe und Grundfarben." Leipzig und Wien: Deuticke, 1898. Reviewed by C. L. Franklin: Psychol. Rev., Vol. 7, 1900, p. 415.

The author "assumes several visual substances, and also, in the end-apparatus of the optic nerve, ultra-microscopic visual elements or corpuscles which are excited, under proper conditions by the visual substances. It is further supposed that the direct action of light upon the visual corpuscles is already sufficient to set them into molecular vibration, and that the effect of the visual substance is simply to modify and to strengthen this vibration. The object of this duplex supposition is to combine in one a photo-chemical hypothesis and a photo-physical one. In the highest animals these substances are three in number, and they give rise to the elementary color sensations.

"The visual elements, corpuscles or threads as they are variously called consist of minute fibers each thickly strewn over its entire surface with projecting flat plates, four in a given plane, and composed of material of four different sorts fitted to respond to four different sorts of stimulus and to furnish three primary color sensations together with the sensation of white. The most characteristic part of the theory is that these little plates are set into molecular vibration in the first instance by the direct action of light (all alike in this case, and attended by the white sensation), but in the second instance this vibration is added to by the synchronous molecular vibrations of the three photo-chemical substances, when severally produced by light of different periodicity. It is then neither the production nor the destruction of a photo-chemical substance that is effective in exciting the nerve terminals, but it is during its relatively brief period of existence that a given substance acts upon the particular color-plate with which it is in harmony."

The various theories outlined in this paper are shown in their mutual relationship to some extent in the accompanying figure. From Newton to Hering the development of color theory proceeded along one main line, the latter originating a new branch which rivals, and, in the opinion of many, completely overshadows the parent stem. By a combination of characteristic features of both Young-Helmholtz and Hering theories, Donders directed development along a third line. At present therefore color theorists are divided into three groups, the physicists conservatively holding to the main line, the psychologists and physiologists, while divided in their allegiance, for the most part accepting the hypothesis of Hering.

The chief theories are criticised from the psychological standpoint in the "Dictionary of Philosophy and Psychology" art. 'Color Vision.' Several are also treated at considerable length in Sir Michael Foster's "Text Book of Physiology," and in Calkins' "Introduction to Psychology," as well as in other works of a similar character. To these and to the critical reviews by Mrs. Franklin which are referred to in their place, as well as to Dr. J. W. Baird of the Department of Psychology, Cornell University, I am indebted for valuable information.

PHYSICS DEPARTMENT, CORNELL UNIVERSITY.

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SOME PHENOMENA OF THE PERSISTENCE OF VISION

By FRANK ALLEN

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SOME PHENOMENA OF THE PERSISTENCE OF VISION.[1]

BY FRANK ALLEN.

THE experiments to be described in this paper were suggested by some discussed in a communication[2] to the PHYSICAL REVIEW some years ago. A full description was there given of the method of measuring the persistence of vision which was first used by E. L. Nichols. The essential features of this method are few and simple. In front of the slit of the spectrometer is placed a sectored disk, which, when rotated by an electric motor, interrupts the light causing a flickering of the part of the spectrum under observation. By electrical means the speed of the disk is recorded on paper on a rotating drum, which enables the duration of a single flash of light upon the eye to be determined when the speed of rotation of the disk is such that the flickering just disappears. The duration of these light impulses varies with the luminosity of the spectrum, and, when plotted with the wave-lengths of the colors observed as abscissæ, gives a persistence of vision curve.

I. It was observed[3] that when the eye is protected from light by being blind-folded or by remaining in a dark room, the time of persistence of all color impressions was increased. Experiments were accordingly made to determine how this effect varied with the time of darkness adaptation. Observations of the persistence of vision were made on four colors, red, yellow, green and blue, after intervals of darkness adaptation of one, three, five, ten and fifteen minutes. The wave-lengths of the colors observed, and other measurements, are given in Table I. and the results are shown graphically in Fig. 1. For convenience in plotting, the ordinates are the differences between the normal readings and those made

[1] Read before the Royal Society of Canada, May, 1908

[2] Frank Allen, PHYS. REV., Vol. XI., 1900, p. 257.

[3] Ibid., p. 265.

after the different intervals of adaptation. The adaptation curves are of the "saturation" type, and show that, as far as the persistence of vision is concerned, darkness adaptation produces its maximum effect in about five minutes, the measurements after the ten and fifteen minute intervals showing no increase over those for five. There is, indeed, an indication in the curves of a partial return to the normal condition of the retina between the five and fifteen minute intervals of adaptation.

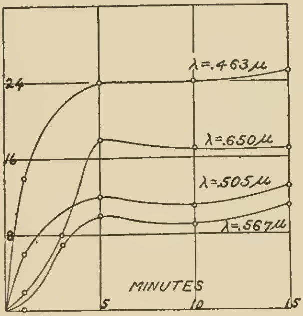

Fig. 1.

It will also be noticed that the maximum is least in the case of the brightest color used ($\lambda = .567\ \mu$), and greatest for the feeblest ($\lambda = .463\ \mu$).

Table I.

Adaptation.	Observation Color.							
	$\lambda = .567\ \mu$.		$\lambda = .505\ \mu$.		$\lambda = .650\ \mu$.		$\lambda = .463\ \mu$.	
Time.	Persistence.	Diff.	Persistence.	Diff.	Persistence.	Diff.	Persistence.	Diff.
Normal.	.0117 sec.	0	.0133 sec.	0	.0135 sec.	0	.0193 sec.	0
1 minute.	.0117 "	0	.0139 "	6	.0137 "	2	.0206 "	14
3 minutes.	.0124 "	7			.0143 "	8		
5 "	.0127 "	10	.0145 "	12	.0153 "	18	.0216 "	24
10 "	.0126 "	9	.0144 "	11	.0152 "	17	.0216 "	24
15 "	.0128 "	11	.0146 "	13	.0152 "	17	.0217 "	25

II. A similar series of curves was obtained after fatiguing the retina by exposure to light of certain definite hues. Readings of the persistence of vision were made after intervals of fatigue of one, two, three, five and ten minutes. Observations were made upon the same, or nearly the same, portions of the spectrum as the fatiguing colors. The measurements are shown in Table II. and are plotted in Fig. 2 according to a convenient scale of numbers so chosen that the curves are all exhibited in one figure. The zero of each curve, which corresponds to the normal persistence of the particular color, is the intersection of the curve with the axis of ordinates.

With all colors the fatiguing effect of the light stimulus reaches its maximum in about three minutes, further exposure to light seeming to make no difference with the duration of light impressions.

TABLE II.

Time of Fatigue.	Observation Color λ = .650 μ. Fatigue Color λ = .675 μ.		λ = .610 μ λ = .610 μ		λ = .575 μ λ = .589 μ		λ = .540 μ λ = .54[illegible]	
	Persistence.	No.	Persistence.	No.	Persistence.	No.	Persistence.	No.
Normal.	.0136 sec.	0	.0123 sec.	12	.0118 sec.	19	.0125 sec.	22
1 min.	.0143	7			.0119	20		
2	.0149	13			.0119	20		
3	.0150	14	.0128	17	.0119	20	.0132	29
5	.0150	14	.0128	17			.0132	29
10			.0128	17	.0119	20	.0132	29

Time of Fatigue.	Observation Color λ = .510 μ. Fatigue Color λ = .523 μ.		λ = .500 μ λ = .500 μ		λ = .485 μ λ = .485 μ		λ = .472 μ λ = .470 μ	
	Persistence.	No.	Persistence.	No.	Persistence.	No.	Persistence.	No.
Normal.	.0126 sec.	24	.0140 sec.	29	.0156 sec.	36	.0165 sec.	42
1 min.	.0128	26					.0165	42
2	.0134	32					.0165	42
3	.0136	34	.0148	37	.0160	40	.0165	42
5	.0136	34	.0147	36	.0160	40		
10	.0136	34	.0148	37	.0160	40	.0165	42

Time of Fatigue.	Observation Color λ = .410 μ. Fatigue Color λ = .413 μ.		λ = .450 μ λ = .450 μ		λ = .45[illegible] λ = .450 μ	
	Persistence.	No.	Persistence.	No.	Persistence.	No.
Normal.	.0334 sec.	50	.0225 sec.	44	.0280 sec.	46
1 min.	.0355	71				
2						
3	.0373	89	.0231	50	.0301	67
5	.0376	92			.0301	67
10	.0374	90	.0231	50	.0301	67

Perhaps the most remarkable curves are those for the yellow and blue colors whose wave-lengths are .575 μ and .472 μ respectively. The latter of these is a straight line, and the former nearly so. For these colors the retina does not seem capable of being fatigued, as the duration of the color impressions always retains its normal value.

The differences between normal and maximum readings of the various curves vary in magnitude, and are shown in Fig. 3. This curve is characterized by three elevations, corresponding to the red, green and violet of the spectrum, which are separated by two depressions corresponding to yellow and blue of wave-lengths .575 μ and .472 μ respectively. It is noteworthy that these two depressions agree with the fundamental yellow and blue of the Hering theory of color vision, while the blue is nearly that chosen by Helmholtz and by König and Diderici (viz. $\lambda = .470\ \mu$) as one of their fundamental colors. The wave-lengths of the maxima of the red and green elevations also are the fundamentals of those colors which have been selected by the last two writers.

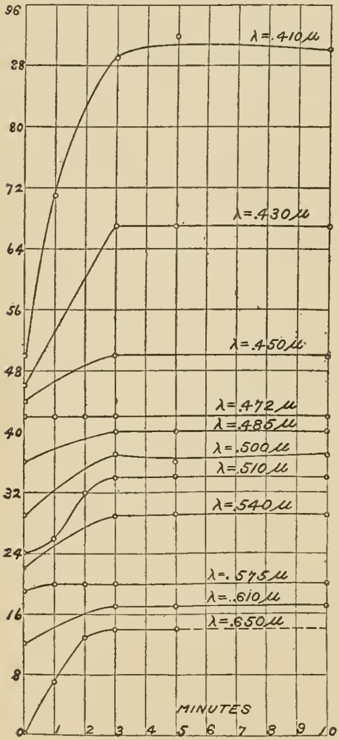

Fig. 2.

This curve with its three elevations seems to support the view that there are but three fundamental color sensations, which correspond to some hues of red, green and violet.

III. It was noticed from time to time that the persistence of color impressions was not constant over all parts of the retina. When no flickering of the color under observation was perceptible in the center of the retina a slight movement of the eye in any direction, which allowed the light to fall upon the peripheral portions of the retina, was always sufficient to destroy the apparent continuity of the light.

To investigate this, a short piece of platinum wire, heated electrically so as to be just plainly visible, was placed in such positions, that, when viewed directly by the eye, the flickering light of the spectrum fell at determinate positions on the outlying parts of the retina.

Two sets of observations were made at two regions on the temporal side of the retina about ten and twenty degrees from the center

Measurements were attempted at other regions farther out, but the results were too uncertain to be of any use.

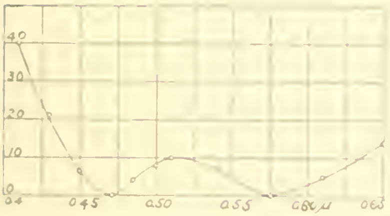

Fig. 3.

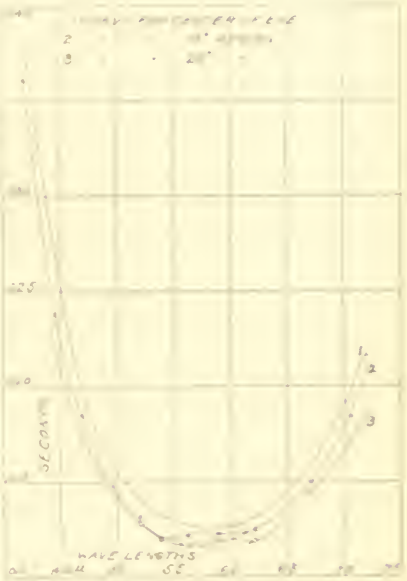

Fig. 4

The measurements are shown in Table III. and are plotted in Fig. 4 in comparison with a curve for the center of the eye.

TABLE III.

λ	Persistence. Center of Retina.	Persistence. 10° Region.	Persistence. 20° Region	λ	Persistence. Center of Retina.	Persistence. 10° Region.	Persistence. 20° Region.
.418 μ	.0372	.0361		.562	.0127	.0122	.0117
.446	.0274	.0238	.0233	.588	.0126	.0123	.0120
.472	.0196	.0185	.0174	.620	.0132	.0125	.0119
.495	.0163	.0148		.670	.0158	.0150	.0144
.520	.0141	.0132	.0128	.705	.0195	.0184	.0170
.538	.0135	.0120	.0120	.720	.0220	.0216	.0185

The curves show that the duration of all color impressions diminishes as the distance from the center of the retina increases; or, in other words, the peripheral portion of the retina is more sensitive to fluctuations in the intensity of the light than the center.

The ten and twenty degree curves show also a remarkable elevation in the part corresponding to the yellow and greenish yellow. In direct vision the light rays fall upon the macula lutea or yellow spot where the greatest distinctness of vision occurs. This spot is, however, small and would not be stimulated by the light falling on the outer regions. As the lowest point of the persistency curve corresponds to the brightest part of the spectrum, the curves show that to the outer regions of the retina under consideration, the most luminous point of the spectrum is nearer the green than it is to the macula lutea.

An elevation in a persistency curve has always been found associated with some induced or natural abnormality of color vision. Here, however, it is found in the normal persistency curves for the outer portions of the retina, and indicates some slight modification in the perception of yellow. The macula lutea contains a yellow pigment and no visual purple, while the retina in other parts has only the visual purple. This latter substance absorbs, and is bleached by, light of all parts of the spectrum but in amounts vary-

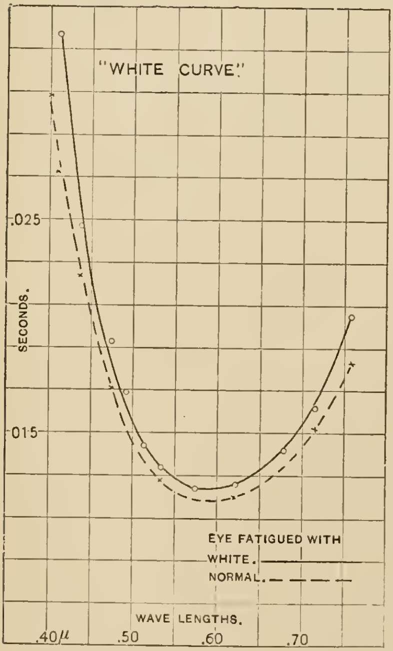

Fig. 5.

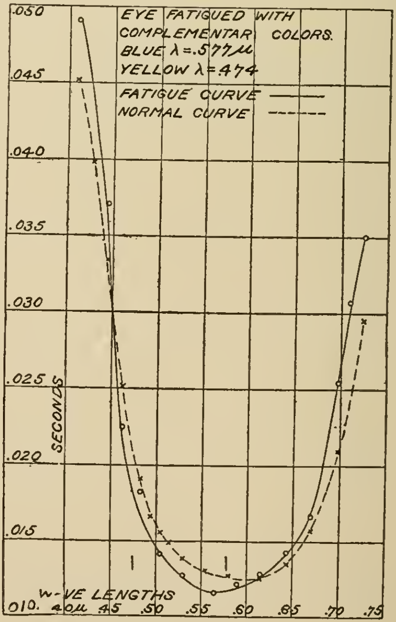

Fig. 6.

ing with the wave-length, the absorption being very slight in the red and greatest in the yellowish green, which has the most rapid bleaching effect. The region of the spectrum, therefore, which is most absorbed by the visual purple coincides with the elevations of the persistency curves.

IV. In the paper to which reference has been made an experiment was described in which a persistency curve was obtained when the eye was fatigued with white light from an electric arc. This curve and its comparison normal curve are shown in Fig. 5 which is reproduced from the paper cited.

As white light, indistinguishable from ordinary white, may be obtained by mixing two complementary colors, observations of the persistence of vision were made after fatiguing the retina with proper combinations of colors. Two overlapping spectra were formed with a Helmholtz color mixer and the selected complementaries combined in a shutter eyepiece. By means of nicol prisms in the collimators the intensities of the two spectra were adjusted until the narrow field of light in the eyepiece was white.

The first pair of complementaries used consisted of yellow ($\lambda = .577\ \mu$) and blue ($\lambda = .474\ \mu$) as determined by von Kries. The readings are given in Table IV., with the corresponding normal values, and the results are graphically shown in Fig. 6.

TABLE IV.

λ	Normal Persistence.	Eye Fatigued $\lambda = .577\ \mu$ $\lambda = .474\ \mu$	λ	Normal Persistence.	Eye Fatigued with $\lambda = .577\ \mu$ $\lambda = .474\ \mu$
.725 μ	.0295 sec.	.0350 sec.	.530 μ	.0138 sec.	.0127 sec.
.710		.0307	.515	.0148	
.698	.0209	.0254	.505	.0155	.0141
.670	.0157	.0166	.495	.0166	
.643	.0135	.0142	.483	.0190	.0182
.615	.0125	.0128	.463	.0251	.0225
.590		.0121	.445	.0334	.0371
.580	.0127		.428	.0398	
.565		.0115	.410	.0451	.0491
.554	.0130				

The second pair of complementaries was red ($\lambda = .656\ \mu$) and green ($\lambda = .492\ \mu$), determined by Helmholtz. The readings of the persistence of vision in this case are given in Table V. and plotted in Fig. 7. The normal curve in this figure is the same as that for the preceding case, given in Table IV.

Table V.

λ	Eye Fatigued with λ = .656 μ λ = .492 μ.	λ	Eye Fatigued with λ = .656 μ λ = .492 μ.	λ	Eye Fatigued with λ = .656 μ λ = .492 μ.
.725 μ	.0353 sec.	.566 μ	.0122 sec.	.470 μ	.0204 sec.
.710	.0335	.548	.0125	.463	.0238
.698	.0230	.530	.0130	.454	.0293
.670	.0161	.517	.0137	.445	.0395
.643	.0136	.505	.0151	.428	.0522
.615	.0122	.492	.0167	.410	.0527
.590	.0120	.483	.0182		

On comparing the figures both curves will be seen to be essentially the same, and to differ greatly from the curve shown in Fig. 5. The fatigue curves obtained with the complementary colors are

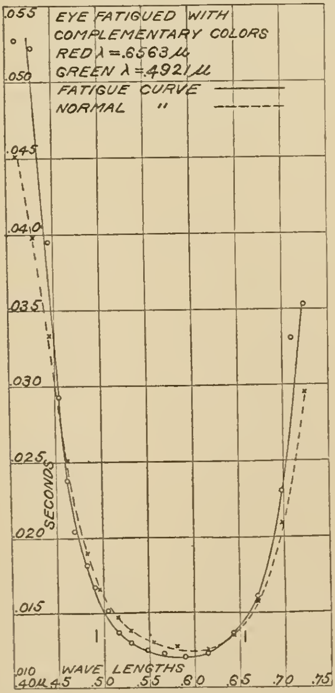

Fig. 7.

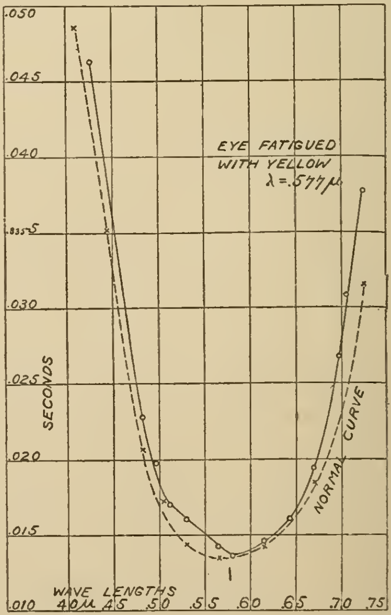

Fig. 8.

elevated above the normal at both ends, which correspond to red and violet, and are depressed below the normal in the middle which corresponds largely to green. The intersections of the curves in each figure (6 and 7) occur in the blue at λ = .455 μ, and in the orange near the yellow, at λ = .62 μ. The effect on the retina of white light of the comparatively few wave-lengths comprised in the complementary colors must of necessity be different from that of the complex mixture of waves forming the white light from an electric arc. The eye is, however, unable to see any difference in the appearance of the two lights when both are of the same intensity; yet measurements of the persistence of vision are capable of showing in a most striking manner the differences in the physiological effects of the two white lights on the retina.

It is most remarkable that the curves in Figs. 6 and 7 are depressed below the normal in the part corresponding to green. For when the eye is fatigued with yellow light (λ = .577 μ) alone, for example, the resulting persistency curve has two elevations, one in the red and the other in the green, as shown in Fig. 8, which is plotted from the data in Table VI.

Table VI.

λ	Normal Persistence.	Eye Fatigued with λ = .577 μ.	λ	Normal Persistence.	Eye Fatigued with λ = .577 μ.
.725 μ	.0315 sec.	.0377 sec.	.566 μ	.0135 sec.	.0142 sec.
.706		.0308	.530	.0144	.0160
.698		.0268	.514	.0156	.0170
.670	.0185	.0194	.497		.0198
.643		.0161	.483	.0206	.0228
.615	.0142	.0146	.445	.0352	
			.427		.0463
.581		.0136	.410	.0486	

No persistency curve has been obtained when the eye was fatigued with the complementary color, blue, of wave-length .474 μ. Fig. 9, however, is a persistency curve obtained when the fatiguing stimulus was another blue, the wave-length of which was .440 μ. This figure is reproduced from the paper previously referred to.

Assuming that the curve for λ = .474 μ would be nearly the same as that for λ = .440 μ, an assumption which is almost certainly correct, it is seen that fatiguing the eye with blue produces two elevations in the curve, one in the violet and the other in the green. It would seem natural to expect the curve obtained when the eye was acted upon by both colors, wave-lengths .577 μ and .474 μ, to have *three* elevations to correspond with those in Figs. 8 and 9.

Instead of this, however, the persistency curve in Fig. 6 shows two elevations and one depression. The anticipated *double* elevation in the green is actually replaced by a depression. As the duration of color impressions on the retina is an inverse function of the luminosity we have the paradoxical conclusion that doubly fatiguing the green sensation with blue and yellow together causes green light to make a more luminous impression than it does normally. Further, since the parts of the curve disturbed by fatiguing the retina with blue and yellow are the red, the green and the violet, it follows that none of the color sensations are independent of each other; while the fact that the curve suffers disturbances in three parts seems to favor the theory of three fundamental color sensations.

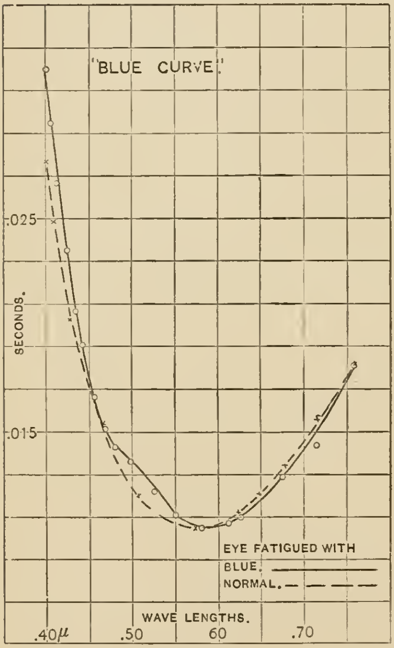

Fig. 9.

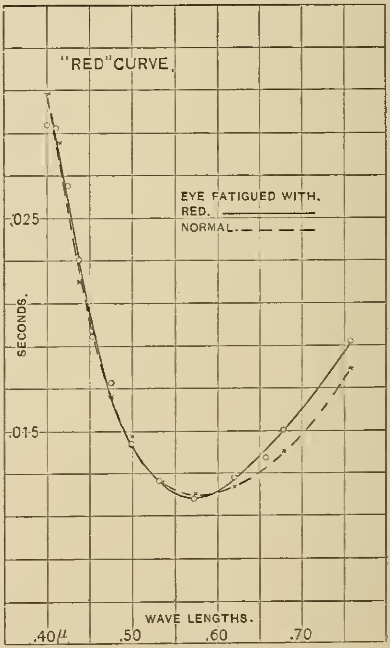

Fig. 10.

The persistency curve in Fig. 7 was obtained, as mentioned before, when the eye was fatigued with red and green of complementary hues. Now when the retina is acted on by red or by green separately a persistency curve is obtained with but one elevation which occurs in the part of the curve corresponding to the color used in fatiguing the eye. This is shown in the curves in Figs. 10 and 11 which are taken from the paper referred to several times.

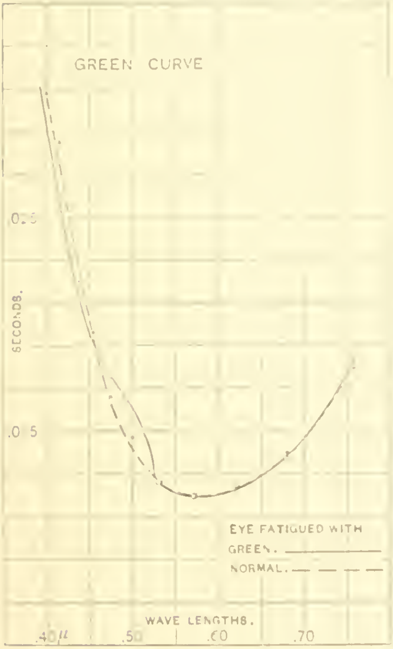

Fig. 11.

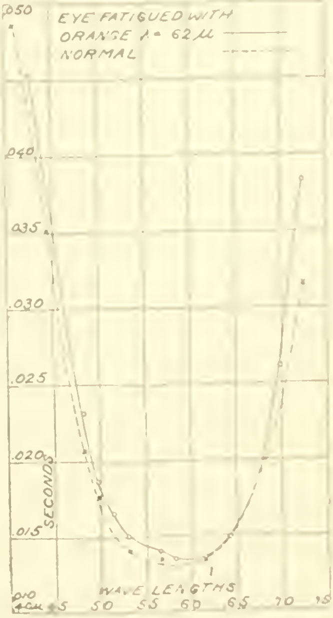

Fig. 12

When, however, the eye is fatigued with complementary red and green colors, the curve (Fig. 7) has an elevation in the red, a *depression* instead of an elevation in the green, and a pronounced elevation in the violet. It is remarkable that there is no green elevation, and still more remarkable that the violet sensation is affected at all, or at least to any very perceptible amount. It is, perhaps, possible that the white light formed by combining complementary red and green hues is a compound with properties of its own quite different from those of the separate components, and, in virtue of its being *white*, stimulates all three sensations, red, green and violet, even though no violet light is present. The same idea would also apply to the curve in Fig. 6, though, as we have seen, the occurrence of the elevations there is susceptible of another explanation.

Both persistency curves obtained when the retina was fatigued by the compounded complementary colors intersect the normal in two places, one in the blue at $\lambda = .455\ \mu$, and the other in the orange at $\lambda = .62\ \mu$. This latter color was used as a fatiguing stimulus and a persistency curve obtained which is plotted in Fig. 12 from the data in Table VII. The curve shows two elevations, one in red and the other in green, indicating the generally admitted composite character of the sensation of orange light.

TABLE VII.

λ	Normal Persistence.	Eye Fatigued with $\lambda = .62\ \mu$.	λ	Normal Persistence.	Eye Fatigued with $\lambda = .62\ \mu$.
.725 μ	.0315 sec.	.0383 sec.	.566 μ	.0135 sec.	.0140 sec.
.706		.0319	.530	.0141	.0151
.698		.0261	.514		.0166
.670	.0185	.0183	.497	.0177	.0186
.643		.0149	.483	.0207	.0231
.615	.0133	.0136	.427		.0453
.581		.0135	.410	.0485	

In general we may conclude that the experiments described in this paper strongly support the view that the fundamental color sensations are red, green and violet.

I desire to acknowledge my indebtedness to the kindness of Professor E. L. Nichols, director of the Department of Physics, Cornell University, in whose laboratory these experiments were performed.

UNIVERSITY OF MANITOBA,
WINNIPEG.

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BY

EDWARD L. NICHOLS

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THE SENSITIVENESS OF THE EYE TO LIGHT AND COLOR

By

T. A. NEELIN, M.A.

OTTAWA
PRINTED FOR THE ROYAL SOCIETY OF CANADA

1913

*The Sensitiveness of the Eye to Light and Color.**

By T. A. NEELIN, M.A.

Presented by PROF. FRANK ALLEN, PH.D., F.R.S.C.

(Read May 28, 1913)

In an extensive paper on "The Luminous Equivalent of Radiation," Nutting† thus summarizes some of the more important characteristics of the visual response to radiation

I. "Sensibility to Slight Differences in Wave Length, has two pronounced maxima, one in the yellow and one in the green, and two slight maxima in the extreme blue and red. These maxima vary considerably with the individual and probably also with the intensity of the radiation used."

II. "Sensibility to Radiation of Varying Intensity.

Sensibility falls off steadily with increasing intensity. It is approximately inversely proportional to the intensity over a wide range. The ratio of optical intensity to intensity of radiation increases more rapidly for red than for blue and green (*Purkinje phenomenon*)."

III. "Sensibility to small Differences in Intensity."

The least perceptible increment measured as a fraction of the whole is approximately:

(1) Independent of Intensity (*Fechner's Law*). It is strictly valid for moderate and high intensities and greater for very low and extremely high intensities.

(2) Independent of Wave Length (*König's Law*) at constant luminosity, extremes again excepted.

(3) Independent of the Individual."

With the exception of number I the above characteristics of the visual response to radiation have been verified by several observers. But concerning the sensibility of the retina to slight changes in the wave-length of the light no investigation of a very exhaustive nature appears to have been conducted. Perhaps the best recent data are those due to Dr. Olga Steindler;‡ but even there a spectrum of only one intensity appears to have been considered. With a view then, in the first place of verifying results already obtained by Steindler and others and in the second place, of investigating the behaviour of these maxima with changes in the intensity of the radiation used, the following observations were made.

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*To be printed also in the Physical Review

†P. G. Nutting: Bulletin of the Bureau of Standards, 1908, Vol. 5, No. 2, page 265.

‡Wien Sitz.: IIa, 115, pp. 1-21, 1906.

When it was found that all of the chief characteristics might be investigated by the apparatus to be used in the case of number I, and in view of the fact that it appeared to be an original method, it was decided to investigate all three cases. It was thought that the accuracy with which the well known phenomena were established might indicate the reliability of the results obtained in the first case.

Historical *

Mandelstamm † appears to have been the first to investigate the color sensitiveness of the human eye for slight differences in the wave length of light observed. By shifting the plates of an ophthalmometer so as to give a just perceptible color difference, he obtained a means of observing sensibility in different parts and obtained in this way maxima of sensibility in the region of the D and F lines. Dobrowolosky ‡ came to the same conclusion by similar means. Peirce[4] investigated the sensitiveness of the eye to slight differences of color by having two identical spectral bands one immediately above the other, the upper one of which might be shifted. The object of the experiment was to see how small a displacement could be infallibly *detected* and *named in direction* by the observer in different parts of the spectrum. He found maxima situated similarly to those found by other investigators. More accurate results were first obtained by König and Dieterici.[5] Uhthoff[6] also investigated the differences in wave length for just observable color differences. Brodhun,[7] himself color blind, gives measurements after the method of König for mean intensities. Exner[8] also gives a single service of measurements on a widely dispersed spectrum. In this connection also Steindler[9] reports observations upon twelve subjects. A spectrum with a dispersion of about 85 cm. at the point observed was obtained by means of an arc light and a concave grating. The light from the spectrum at this point fell upon two totally reflecting prisms placed vertically one above the other and after reflections from a second larger prism two adjacent fields appeared in the eye-piece. Since the upper of the two smaller prisms was movable along a horizontal scale light of the same or slightly different wave-length might be caused to the field. In this way the amount of change necessary to produce a just perceptible but distinct color difference was measured. Values thus obtained were mean values for at least ten observations made by the same person on the same portion of the spectrum.

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*Historical references taken from Dr. Steindler's paper.

†Grafe's Archiv: Bd. 13, p. 399.

‡Ebenda, Bd. 18, p. 99.

[4] American Journal of Science, Vol. 26 (1883), p. 299.

[5] Annalen der Physik und Chemie, Bd. 22, p. 579.

[6] Grafe's Archives, Bd. 34, 4, p. 1.

[7] Zeitschr. für Psych. und Phys. Bd. 34 (1892), p. 89.

[8] L. c. p. 875.

[9] Wien Sitz.: IIa, 115, pp. 1-24, 1906.

Description of Apparatus.

One arrangement of apparatus was found sufficient for all investigations and is essentially that used by Allen* to measure the luminosity of the spectrum. The general arrangement is shown in Fig. 1. The light from an acetylene flame A after concentration by lenses B and B¹, passed through the opening C from a light proof chamber M, then through two nicol prisms (E and F) arranged with their principal sections horizontal; thence through the spectrometer G and was finally viewed in a Hilger eye-piece H in which all the light of the spectrum except a narrow central band was cut off by means of adjustable shutters. The observer was therefore able to subject his eye to a light stimulus of any desired wave-length. A constant gas pressure was taken to indicate a constant luminosity in the source of light. The intensity of the spectrum was controlled by rotating the polariser. The principal plane of the analyser remained horizontal for all investigations in order that the displacement of the light waves as they met

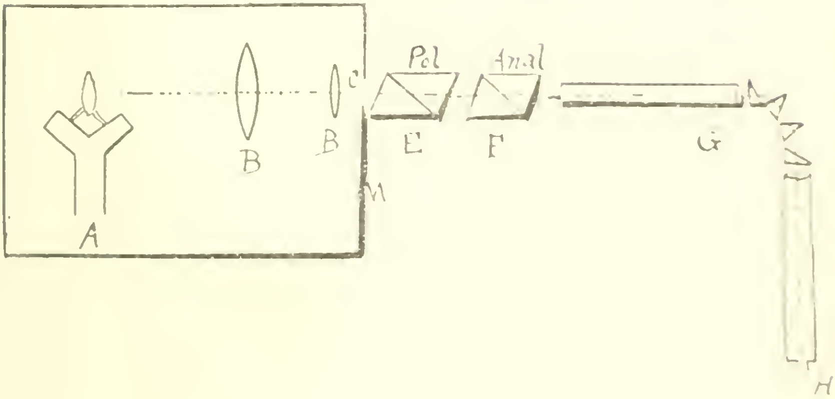

Fig. 1.

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*Frank Allen: Phil. Mag. 1911. Vol. 21. No. 125. page 604.

the prism might be perpendicular to its face. In this way it was thought to avoid a variation in intensity of light through reflection from the surfaces of the prisms.

The spectrometer used was of the Hilger Automatic type with four prisms equivalent to three sixty degree prisms and giving a dispersion slightly in excess of twelve degrees.

I.

Each characteristic of the visual response to radiation as outlined in the commencement of this paper, was treated as a separate investigation. Observations were made to show:

1. Whether sensibility to slight difference in wave length has two pronounced maxima, one in the yellow and one in the green, and two light maxima in the extreme blue and red.

2. Whether these maxima vary with the intensity of the radiation used.

1. In the investigation concerning spectra of varying intensity, other conditions remaining constant, spectra of six different intensities were examined. Only observations made with my own eye (the right) which seems quite normal as to color sensations, are considered in this paper. Upon the spectrum of maximum intensity in all parts, which for present purposes, has been represented by unity, and upon a spectrum of intensity ·25, observations were made to determine the minimum *decrease* in intensity by which the initial intensity was changed in effecting a change in sensation that was just perceptible. In the case of spectra at all other intensities considered, the minimum *increase* in the original intensity necessary to produce a just perceptible change in the sensation was determined.

Method of procedure.

The principal sections of the nicols were horizontal and so gave the brightest spectrum obtainable with the chosen arrangement of apparatus. Observations were made upon thirty-two portions of this spectrum; these are given in Table I.

Light of wave length $\cdot 42\mu$ was first observed. This was allowed to act upon the retina for four seconds. Then the polariser was rotated at a uniformly rapid rate; an effort was made to keep the rate at which the polariser was rotated, approximately constant for all observations. As soon as a change in the sensation of light was perceived the rotation was stopped. The angle through which rotation had taken place was noted. This was denoted by α; since unity had been taken to represent the amount of light passing through the prisms before the polariser was rotated, the difference between 1 and $\mathrm{Cos}^2\,\alpha$ i.e., $\mathrm{Sin}^2\,\alpha$ will represent the amount by which the original intensity of the light was *diminished* in effecting a change of sensation that was just perceptible. The reciprocal of this value ($\sin^2 \alpha$) taken to represent the sensibility of the eye has been plotted as a function of the corresponding wave length. This is shown in Curve I, Fig. 2. The other chosen portions of the spectrum were observed in rapid succession in a similar way.

A dimmer spectrum was next considered. This was obtained by setting the polariser before each observation so that its principal plane made an angle of 51° with the horizontal, i.e. with the plane of the analyser. This initial angle was denoted by β. Since $\mathrm{Cos}^2\,\beta = \mathrm{Cos}^2$ 51° is equal to ·395, it was considered that each portion of the spectrum chosen for investigation was 39·5% of the intensity of corresponding portions in the spectrum at maximum intensity. With this initial arrangement light as observed in the eye-piece was, as before, allowed to act upon the retina for four seconds. Then the polariser was rotated so as to *increase* the intensity of the light. As soon as the intensity had just noticeably increased the rotation was stopped. The angle between the planes of the nicols was read and denoted by α. Since Cos^2 51° represents the intensity of the stimulus at the beginning and $\mathrm{Cos}^2\,\alpha$ the intensity of the light affecting the eye at the moment of perceptible change, $\mathrm{Cos}^2\,\alpha - \mathrm{Cos}^2$ 51° will represent the amount by which the original intensity (which for each observation is 39·5% of the maximum intensity of the spectrum at the chosen point) was *increased* in affecting a change of sensation that was just perceptible. As before, the reciprocal of this value was taken to represent the sensibility of the eye and has been plotted as a function of the corresponding wave length. The results are shown graphically in Curve II, Fig. 2. The portions of the spectrum observed and the observations made upon each are given in Table II.

Upon the spectrum of intensity ·25 observations were made to determine the least perceptible *decrease* in the initial stimulus necessary to produce a noticeable change in the sensation of light. This was done by following the method described for the spectrum at maximum intensity. The results are given in Table III and are shown graphically in Curve III, Fig. 2. The spectrum of intensity ·25 was obtained by setting the plane of the polariser at an angle of 60° with the plane of the analyser.

In the case of other spectra investigated observations were made for the least perceptible *increase* in the initial stimulus, following the method used upon the spectrum second in order of brightness, as described above. These spectra were of relative intensities ·060; ·025 and ·0054 respectively,—the spectrum of maximum intensity being

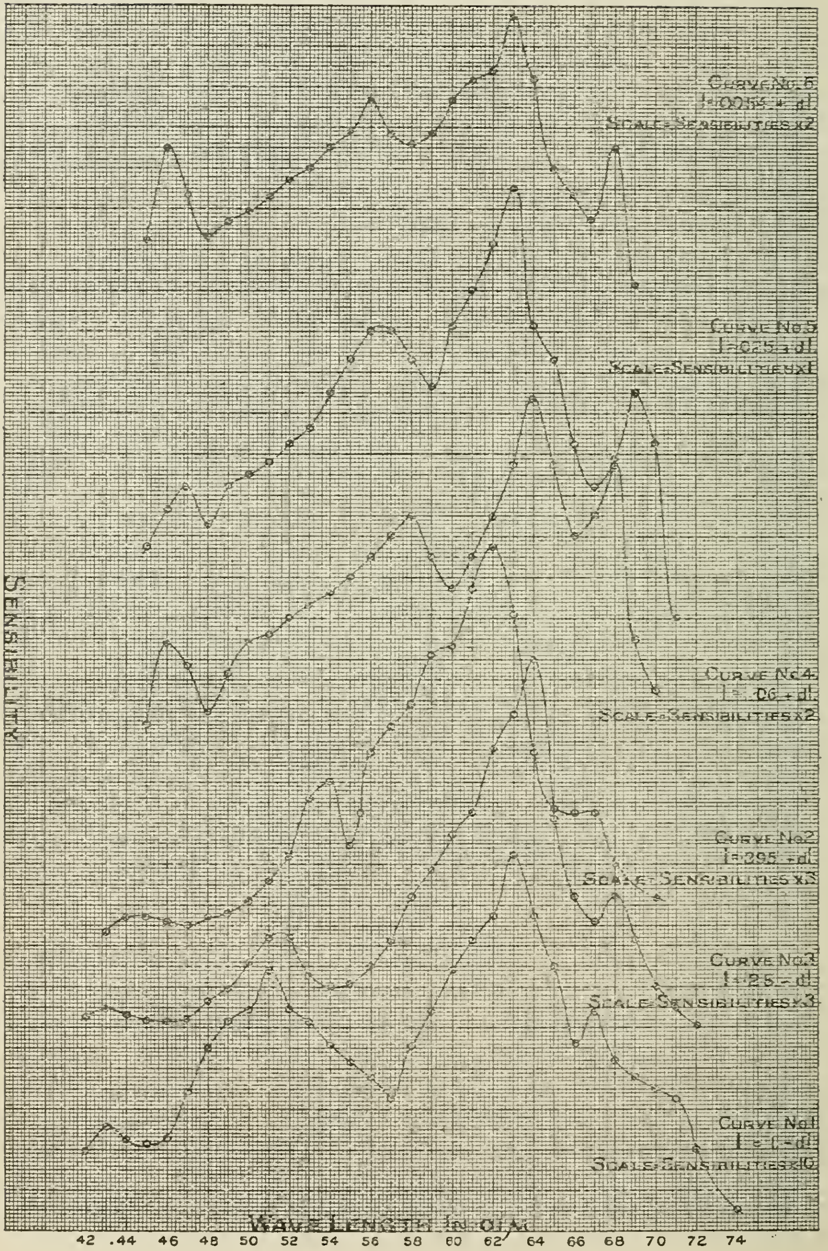
Curve No. 6
I = .0055 + dl
Scale = Sensibilities x2
Curve No. 5
I = .025 + dl
Scale = Sensibilities x1
Curve No. 4
I = .06 + dl
Scale = Sensibilities x2
Curve No. 2
I = .295 + dl
Scale = Sensibilities x5
Curve No. 3
I = .25 – dl
Scale = Sensibilities x3
Curve No. 1
I = 1.0 – dl
Scale = Sensibilities x10
Sensibility
Wave Length in 0.1 μ
42
.44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74

Figure 2

considered as equal to unity in all parts. The initial intensities to give spectra of such intensities for each observation were the inclinations of the principal planes of the nicols to each other at angles of 75° 45′, 80° 45′ and 85° 45′ respectively. The results are given in Tables IV, V and VI and shown graphically in Curves IV, V and VI, fig. 2.

Tables of data.

In Tables I to VI λ indicates the wave length of light observed. The column headed "Scale Readings" gives the observed reading on the attached scale, after each rotation. With each new intensity the zero of the scale was observed and taken into account to find the angle between the principle sections of the nicols. These values will be found in the column headed α. Since β denotes the initial angle between the principal sections, in the column under $\mathrm{Cos}^2\beta$ will be found the intensity of the spectrum considered in each case. In the column under $\mathrm{Sin}^2\alpha$ Table I and under $\mathrm{Cos}^2\beta-\mathrm{Cos}^2\alpha$ Table III will be found the amount by which the initial intensity was *diminished* to effect the minimum noticeable change of sensation. In Tables II and IV to VI, under $\mathrm{Cos}^2\alpha-\mathrm{Cos}^2\beta$ are given the amounts by which the original intensity (as shown under $\mathrm{Cos}^2\beta$) had to be increased to effect a change of sensation just perceptible. Under "Sensibility" are the values of the reciprocals of the amounts of minimum perceptible change in intensity. In order that the various curves might be plotted in one figure these reciprocals, which are the ordinates for the different curves, have been multiplied by arbitrary constants as indicated in the figure and then plotted to the scale shown.

2. A *Spectrum of Equal Luminosity in all parts.*

When measuring the luminosity of the spectrum Allen* took observations upon nineteen portions of it, determining in each case the angle which the principal plane of the polariser should make with the horizontal, i.e., with the plane of the analyser in order that each portion as viewed in the eye-piece should have equal luminosity. Therefore since the apparatus used in the present investigation was also used by Allen in approximately the same arrangement with the same gas jet, gas pressure and slit width, it was considered that, by observing these same portions and setting the plane of the polariser at the corresponding angle for each, equality of luminosity in the parts observed would be obtained. This would it was thought be equivalent to observing a spectrum of equal luminosity in all parts. The next problem considered, then, was that of determining the sensibility of the eye to slight differences in intensity when the light stimulus was of equal intensity at each point of observation. For this purpose observations similar in principle to those already described, were made upon this "Equivalent of a Spectrum of Equal Luminosity."

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*Phil. Mag., 1911, Vol. 21, p 604

Method of procedure.

The method of procedure was first to adjust the telescope of the spectrometer for light as near the ultra-violet as it was possible to make an observation. This was of wave length $\cdot 460\mu$. The plane of the polariser was adjusted to make an angle of 35° with the plane of the analyser. This gave to the light as viewed in the eye-piece a luminosity equal to the luminosity of the spectrum where the light waves were $\cdot 414\mu$—the principal sections of the nicols then being parallel. This latter luminosity was taken as the standard of brightness since all portions observed were first reduced to this luminosity. After the manner of former observations the light as viewed in the eye-piece was allowed to act upon the retina, the polariser rotated and the angle after rotation noted. This angle was denoted by α. If β denote the initial angle (35°) between the planes of the nicols, then since α was taken to denote the angle between the planes after rotation, $(\mathrm{Cos}^2\alpha - \mathrm{Cos}^2\beta)$ will be proportional to the amount of light by which the initial intensity was *increased* to effect a noticeable change in the sensation. *This amount of light* $(Cos^2\alpha - Cos^2\beta)$, *will be a fraction of the total intensity at the point considered.* But since the luminosity of each part was reduced to that of the standard, it is reasonable to expect that, at those points where the spectrum is brighter and therefore more intense, a smaller portion of the total intensity will be required to produce a noticeable change in the sensation than will be required where the total brightness is much less. That is: the brighter the spectrum at the point of observation the smaller the fraction of total intensity necessary to effect a noticeable change in the sensation. Hence we may say that the luminosity of each part of the spectrum is inversely proportional to the portion of total intensity required to effect a noticeable change in the sensation—the sensation in each case being the result of a light stimulus varying only in wave length. Therefore, plotting the reciprocals of the various values of $(\mathrm{Cos}^2\alpha - \mathrm{Cos}^2\beta)$ as functions of the corresponding wave lengths a luminosity curve for the spectrum should be obtained. This is shown in Fig. 3.

In the above case the reciprocals of the various portions of total light added cannot represent sensibility because in one instance we may take the reciprocal of a large quantity of light at low intensity and

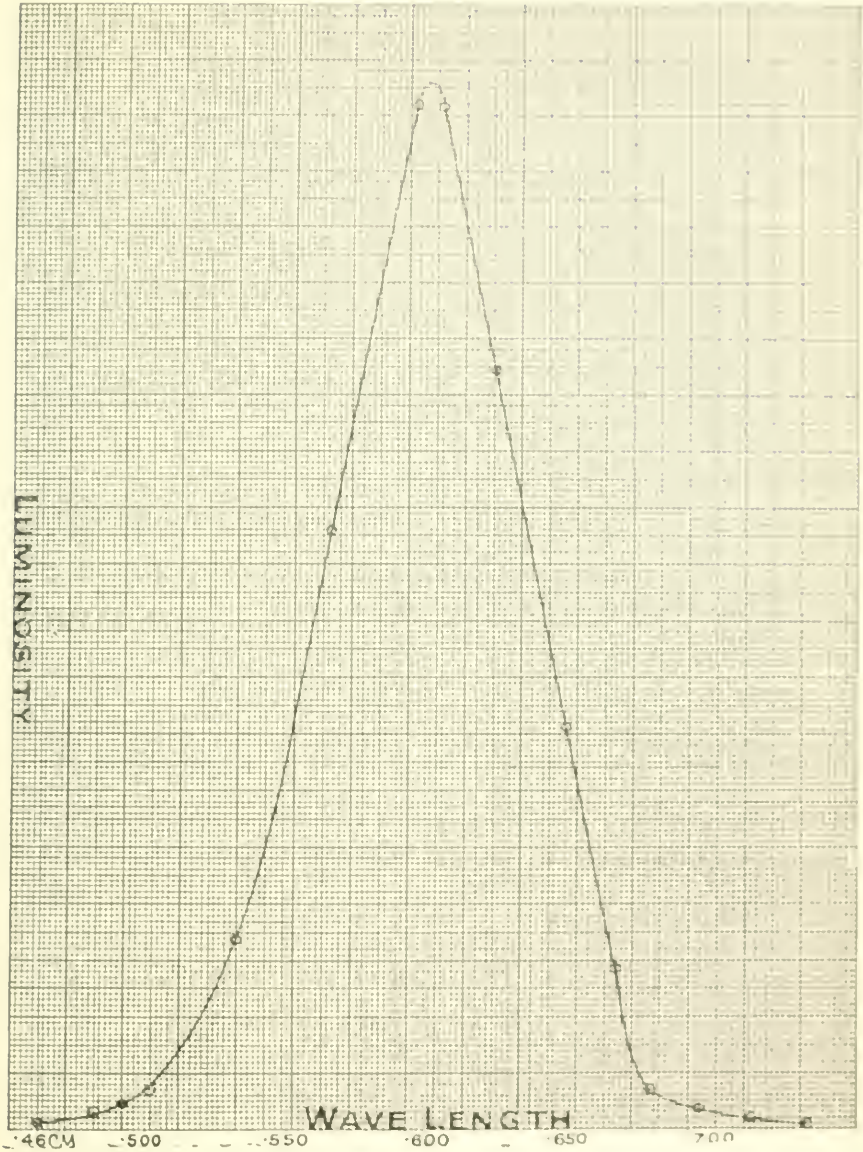

Figure 3

in another the reciprocal of a small quantity at high intensity. And while the reciprocals differ vastly in value the actual illuminating power of the two quantities may be indentical. In the one the increment of light was added at low intensity and therefore more of it was required; in the other it was added at high intensity and less of it was required. Hence before calculating reciprocals for the purpose of showing sensibility, the various increments of light were first reduced to a common standard of intensity. This was the intensity of the standard of brightness, viz., the intensity of light of wave length $\cdot 414\mu$ as observed in the eye-piece while the principal sections of the nicols were parallel.

Method of Reducing to a Common Standard of Intensity.

We may assume that the luminosity of any portion of the spectrum is proportional to its intensity. But the luminosity is inversely proportional to the fraction of total intensity, at the point considered, that will give a luminosity equal to the luminosity of the standard of brightness. But this fraction of total intensity is proportional to the square of the cosine of the angle between the principal sections of the nicols—the light going through giving a luminosity equal to the luminosity of our standard of brightness. That is: the luminosity of any portion of the spectrum is inversely proportional to the square of the cosine of the angle between the principal sections of the nicols when the light going through from that portion gives a luminosity equal to that of the standard. Therefore, taking the luminosity of the standard as unity, the luminosity of the spectrum at any point considered in terms of this standard is given by $1/\cos^2\beta$ where β is the angle between the principal sections of the nicols when just sufficient of the light considered is going through to give a luminosity equal to the luminosity to the standard. And since intensity is assumed proportional to luminosity, the intensity of light at any point in the spectrum in terms of the intensity of the standard is given by $1/\mathrm{Cos}^2\beta$.

Again, α denotes the angle between the principal sections of the nicols after the rotation already explained. Therefore, the fraction of total intensity by which the initial intensity i.e., that represented by $\mathrm{Cos}^2\beta$, was increased to give the least perceptible change in the sensation, may be represented by $(\mathrm{Cos}^2\alpha - \mathrm{Cos}^2\beta)$. The intensity of any given portion of light depends upon its position in the spectrum. Therefore, the fraction of total intensity will have an intensity depending upon the position of the point in the spectrum at which it was added, i.e. depending upon the value of the angle β. But it has been shown that the intensity of light from any portion of the spectrum may be expressed in terms of the standard of brightness by multiplying by $1/\mathrm{Cos.}^2\beta$. Henceit was thought that by multiplying $(\mathrm{Cos}^2\alpha - \mathrm{Cos}^2\beta)$ by $1/\mathrm{Cos}^2\beta$ the various increments of light added to produce a perceptible change in the sensation in each case would be of equal intensity i.e., they would have an intensity equal to the intensity of the light in the standard. The reciprocal of this product it was thought would represent sensibility. The portions of the

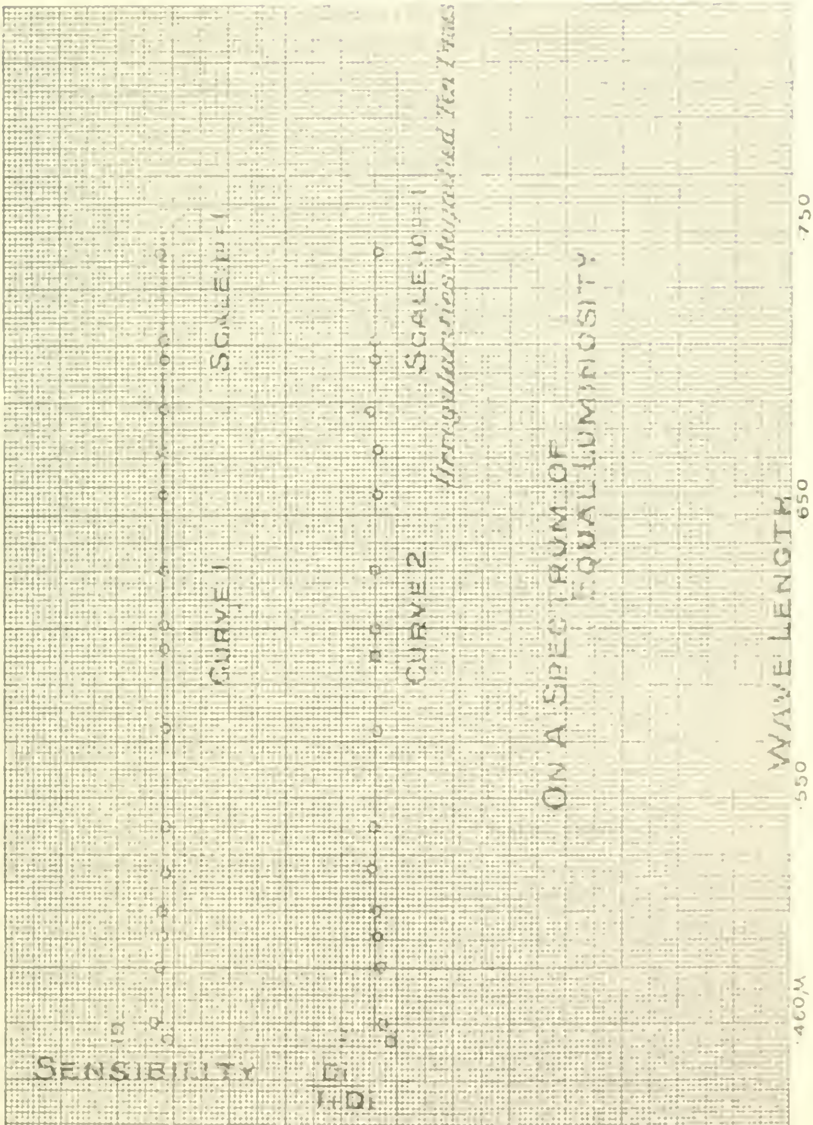

Figure 4

spectrum observed with the corresponding data and calculations are given in Table XV. The sensibility in each case was plotted as a function of the corresponding wave length as shown in Curve 1, Fig. 4.

thus showing sensibility to slight differences in intensity using the equivalent of a spectrum of uniform luminosity.

Table of data.

In Table XV, λ indicates the portion of the spectrum upon which observations was made. "β" denotes the inclination of the plane of the polariser to the plane of the analyser. In the column under "α" will be found the inclination of the plane of the polariser to the plane of the analyser *after rotation has taken place.* $\mathrm{Cos}^2\beta$ will represent the amount of light going through the nicols before the rotation of the polariser, and $\mathrm{Cos}^2\alpha$ the amount of light going through when this rotation was completed. In the column under "Least Perceptible Increments" will be found the value of $(\mathrm{Cos}^2\alpha - \mathrm{Cos}^2\beta)$ which will represent the fraction of total intensity which had to be added to the initial intensity $(\mathrm{Cos}^2\beta)$ to effect a change of sensation that was just perceptible. The reciprocals of those values plotted as a function of the corresponding wave length gave the luminosity curve found in Fig. 3. As explained above those increments were reduced to light of uniform intensity by dividing by $\mathrm{Cos}^2\beta$ in each case. The reciprocals of these latter results were taken to represent sensibility and will be found under "Sensibility." Under $Di/(I+Di)$ will be found the value of the least perceptible increment divided by the total intensity (after rotation) which was used to get curve 2, Fig. 4 to demonstrate König's Law.

II.

Sensibility to Radiation of Varying Intensity.

As a demonstration of the steady falling off of sensibility with increasing intensity and to show that it is approximately inversely proportional to the intensity over a wide range, observations were made as follows:

The same apparatus as used in the preceding was used in this; and the same arrangement. First, the telescope of the spectrometer was adjusted for light of a given wave length, for example $\cdot 420\ \mu$ (see Table VII), and rigidly fixed. The nicols were then crossed so as to exclude all light from the eye-piece. The angle indicated on the attached scale was read and this reading was taken to indicate an inclination of 90° between the principal sections of the nicols. The polariser was then rotated and at the first sensation of light experienced through the eye-piece, rotation was stopped. The angle indicated on the attached scale was again read. Let $\alpha_{,1}$ denote this angle which is necessarily less than 90°. Now $\text{Cos}^2 90 = 0$ and $\text{Cos}^2 \alpha_1$ which is slightly greater than 0 will, as explained in the fore part of this paper, represent the amount of stimulus necessary to produce a sensation of light. This amount of light ($\text{Cos}^2 \alpha_1$), as an initial stimulus was allowed to fall upon the retina and the polariser *further* rotated. As soon as the sensation of light as experienced from the initial stimulus was perceived to change rotation was again stopped, and the angle indicated on the scale read. If α_2 denote this angle, $\text{Cos}^2 \alpha_2$ will represent the amount of light going through the nicols *when rotation was stopped.* But $\text{Cos}^2 \alpha_1$, represents the amount of light going through the nicols *before the last rotation began.* Therefore ($\text{Cos}^2 \alpha_2 - \text{Cos}^2 \alpha_1$) will represent the amount of light by which the initial stimulus ($\text{Cos}^2 \alpha_1$) was increased to produce a change in the sensation that was just perceptible. Observing again the amount of light now in the eye-piece ($\text{Cos}^2 \alpha_2$) and further rotating the polariser until as before another change of sensation was experienced we obtained the angle α_3. Since in this case $\text{Cos}^2 \alpha_2$ represents the initial stimulus ($\text{Cos}^2 \alpha_3 - \text{Cos}^2 \alpha_2$) will represent the increment of light necessary to produce a change of sensation that was just perceptible. In this way the light going through the nicols at the end of each observation was the light upon which each subsequent observation was made until full brightness was reached. That is: the intensity of light used for any observation is represented by $\text{Cos}^2 \alpha_n$ and the increment added by ($\text{Cos}^2 \alpha_{n+1} - \text{Cos}^2 \alpha_n$) where n represents the number of observations made from the crossing of the prisms. In this way several portions of the spectrum were examined. The radiation observed in each portion varied only in intensity and hence the sensibility to radiation of varying intensity was obtained. The reciprocal of ($\text{Cos}^2 \alpha_{n+1} - \text{Cos}^2 \alpha_n$), taken to represent sensibility, was plotted as a function of the corresponding initial intensity, $\text{Cos}^2 \alpha_n$. The results are shown in Fig. 5. The radiation used in obtaining the different curves is indicated in the figure. The portions of the spectrum observed with the data obtained and the calculations made from them are given in tables VII, VIII, X, XII, XIII and XIV.

Starting with the spectrum at maximum brightness and observing the least perceptible decrease in intensity at each step till complete darkness was reached, data were obtained from which the curves indicated in Fig. 5 as "curves of decrements," have been plotted. These data are to be found in Tables IX and XI. These curves seem to indicate that the *increase* in sensibility with *decreasing* intensity follows the law for *decreasing* sensibility with *increasing* intensity.

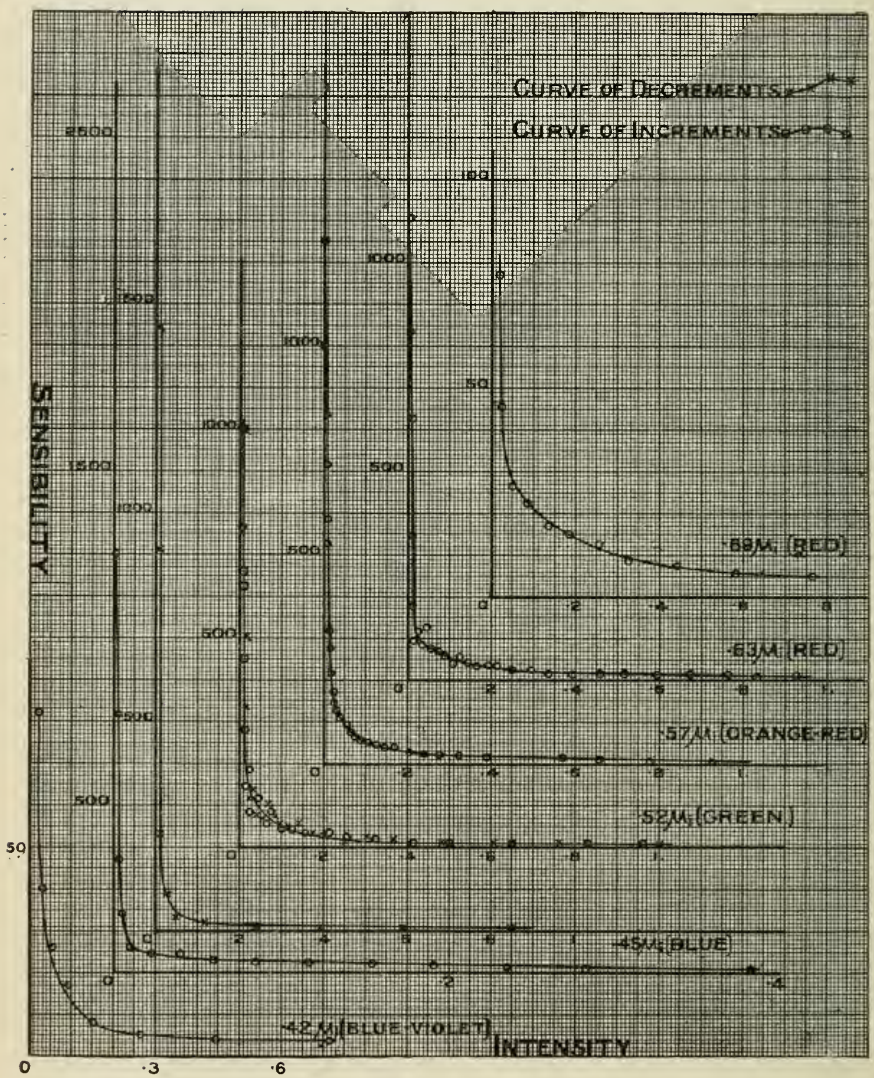

Figure 5

Tables of Data.

In Tables VII to XIV "α" indicates the angle between the planes of the nicols for each observation; "Cos²α" the intensity of the light upon which the observation was made. In Tables IX and XI "Least perceptible decrement" is the amount by which the intensity of the light "Cos²α" was *diminished* in effecting a change in the sensation that was just perceptible. In the other tables of this part "Least perceptible increment" is the amount by which the intensity of the light was *increased* in effecting a change of sensation that was just perceptible. "Sensibility" is the value of the reciprocal of the least perceptible increment, or decrement, as the case may be.

III.

Sensibility to small differences in Intensity.

1. Without further observation it may be shown from the data in Tables VII to XIV that the least perceptible increment or decrement measured as a fraction of the whole is approximately independent of intensity.

It has already been shown (II) that, with any constant wave length, the intensity of the light used for any observation say, the nth, may be represented by $\text{Cos}^2 a_n$ and the least peceptible increment by $(\text{Cos}^2 a_{n+1} - \text{Cos}^2 a_n)$. Let

$$\frac{\text{Cos}^2 a_{n+1} - \text{Cos}^2 a_n}{\text{Cos}^2 a_{n+1}} = \text{k or } \text{Cos}^2 a_{n+1} - \text{Cos}^2 a_n = \text{k Cos}^2 a_{n+1}$$

There appears to be a difference of opinion as to whether the denominator here should be $\text{Cos}^2 a_n$ or $\text{Cos}^2 a_{n+1}$. Substituting the proper values for a_n, curves have been plotted as shown in Fig. 6. It was impossible in some cases to mark all points on the curve because of their coming so close when the intensity was low and so representative points are shown.

2. Again, from the data given in Table XV it may be shown whether "the least perceptible increment measured as a fraction of the whole is approximately independent of the wave length (König's Law) at constant luminosity." For since the data given in this table were obtained by making observations upon different portions of what was thought to be the equivalent of a spectrum of uniform luminosity, we may infer that while the wave length varied with each observation, the intensity of the light as observed in the eye-piece of the spectrometer remained constant for all observations. Take for example, the data furnished by the third observation in the table referred to above. It is shown there that the amount of light going through the nicols at the beginning of the observation is represented by ·1170, while the amount of light going through at the end of the observation is represented by ·1849 showing that ·0679 of the total intensity of the spectrum where the wave length equaled ·491μ, had to be added to

·1170 of total intensity to produce a change in the sensation that was just perceptible. This portion of light reduced to the intensity of the standard of brightness at the polariser was found to be represented

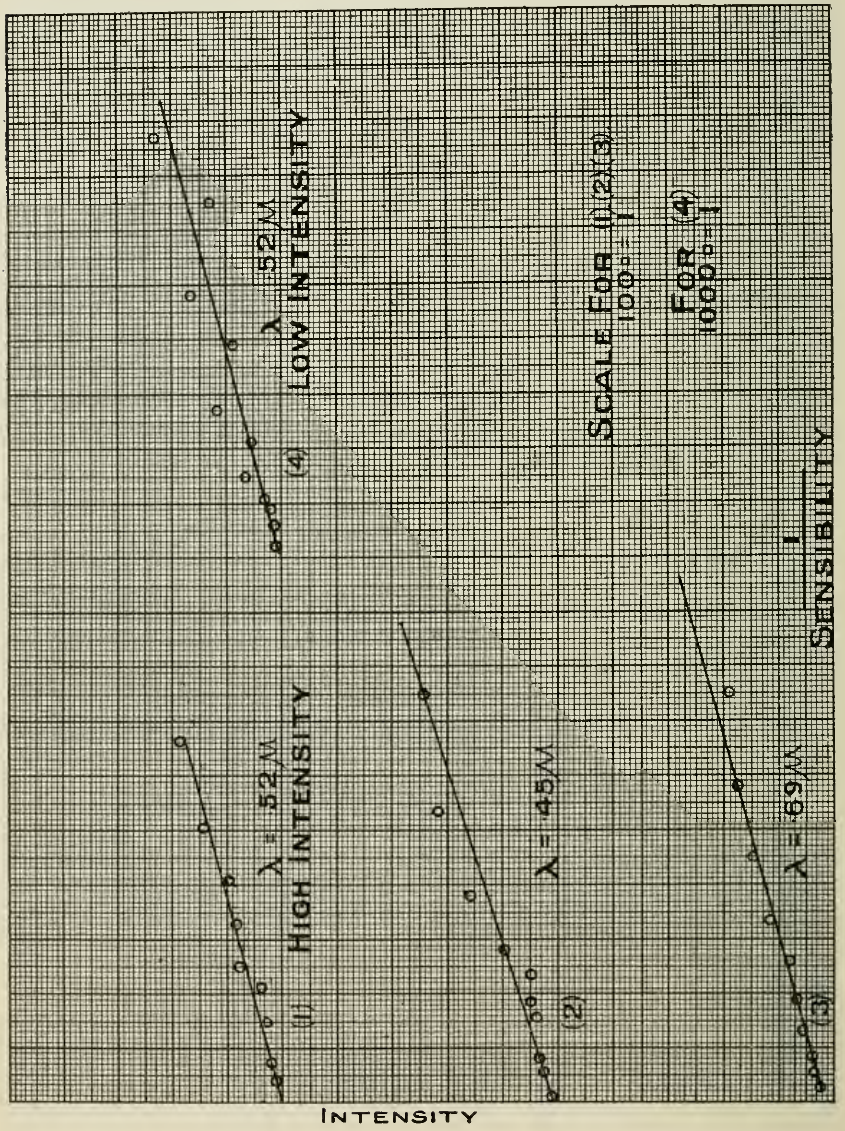

Figure 6

by ·58 as shown in the table, which gives us the least perceptible increment with an intensity at the polariser equal to the intensity of the standard. Now, as already stated, the intensity of the light under observation is represented by ·1170 of the total intensity of the spectrum in portion observed. But this fraction of total intensity gives a luminosity in the eye-piece equal to the standard of brightness which in this paper is represented by unity, and all portions of the spectrum, as observed, were of equal brightness. Therefore we may represent the luminosity of each of those portions by unity, and hence also their intensities as observed in the eye-piece by unity. Now König's Law stated mathematically is of the form $Di/(I + Di) = k$, where Di represents the least perceptible increment and I a constant intensity in the source of light as first observed. Hence making the proper substitutions in the above formula from data in Table XV and plotting, Curve 2, Fig. 4 was obtained.

Discussion of Results.

In general, we may conclude that the experiments described in part I of this paper strongly support the view that, except in the case of spectra from light at very low intensity, the general character of the sensibility curve does not vary with varying intensity of the source. If, however, the spectrum is one of very low intensity the two pronounced maxima, one in the yellow and one in the green tend to diminish while the two slight maxima in the blue and red apparently maintain their prominence. When the spectrum is of uniform intensity in all parts these maxima appear either to disappear entirely, leaving a uniform curve parallel to the horizontal axis, or to become scarcely more than noticeable. Referring to Table XV it will be noticed that in the regions of $\mu = ·564$ and $\mu = ·648$ slight maxima still persist. I do not know whether these indications have a real physical significance or are due to inaccurate observations. I am inclined to adopt the latter reason for their appearance. This could only be settled absolutely by the work of several observers upon uniform spectra at different intensities. If, indeed, these maxima really exist in however slight a degree, we are forced to conclude that König's Law as interpreted in this paper is not *absolutely* correct, for these maxima still persist as is shown under $Di/(I + Di)$, Table XV. Conclusions reached regarding the steady fall in sensibility with increasing intensity, and the application of Fechner's Law, are quite in accord with accepted results.

I desire to acknowledge my indebtedness to the kindness and valuable advice of Professor Frank Allen, director of the Department of Physics, University of Manitoba, at whose suggestion the investigations described in this paper were undertaken; also to Dr. R. K.

McClung of the same department for valuable discussions and kind interest shown. The method employed is also due to Professor Allen.

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Note.—A most comprehensive study conducted by Dr. H. E. Ives and several assistants, has lately appeared in a series of five papers (Phil. Mag., Vol. 24, 1912, pp. 149-188; 352-370; 744-751; 845-863) under the general title "Studies in the Photometry of Lights of Different Colors." Because of the fact that the writing of the present paper was completed before the publication of Dr. Ives papers no reference has been made to them. I should like to point out however, that, though in obtaining the Luminosity Curve for the Spectrum, I was dependent upon other means to get a spectrum of uniform luminosity, the human eye when undisturbed by the presence of a second color is capable of distinguishing changes in luminosity to a very fine and uniform degree of sensitiveness as is shown by the smoothness of his luminosity curve.

TABLE I.

λ	Scale Reading		a		Sin$^2 a$	Cos$^2 \beta$	Sensibility
·42μ	34°	'	24°	'	·1648	1·	6·04
·43	33		23		·1521		6·55
·44	33	30	23	30	·1584		6·31
·45	35		25		·1780		5·64
·46	33	30	23	30	·1584		6·31
·47	31	30	21	30	·1339		7·44
·48	30		20		·1169		8·55
·49	29	30	19	30	·1108		9·17
·50	29		19		·1056		9·46
·51	28	30	18	30	·1004		9·94
·52	29		19		·1056		9·46
·53	29	30	19	30	·1108		9·17
·54	30		20		·1169		8·55
·55	30	30	20	30	·1225		8·16
·56	31		21		·1281		7·8
·57	32		22		·1398		7·25
·58	30		20		·1169		8·55
·59	29		19		·1056		9·46
·60	28		18		·0954		10·48
·61	27	30	17	30	·0900		11·11
·62	27		17		·0852		11·73
·63	26		16		·0756		13·33
·64	27		17		·0852		11·73
·65	28		18		·0954		10·48
·66	30		20		·1169		8·55
·67	29		19		·1056		9·46
·68	30	30	20	30	·1225		8·16
·69	31		21		·1281		7·80
·70	31	30	21	30	·1339		7·44
·71	32		22		·1398		7·25
·72	34		24		·1648		6·04
·73	38		28		·2199		4·54

TABLE II

λ	Scale Reading	α	Cos²α	Cos²β	Cos²α − Cos²β	Sensibility
·43μ	47° [illegible]′	38° 4[illegible]′	·611	·395	·216	4·6
·44	50	41	·568		·173	5·7
·45	50	41	·568		·173	5·7
·46	49	40	·586		·191	5·2
·47	48 [illegible]	39 [illegible]	·594		·199	5
·48	49 [illegible]	40 [illegible]	·577		·182	5·4
·49	50 [illegible]	41 [illegible]	·559		·164	6
·50	51 [illegible]	42 [illegible]	·543		·148	6·7
·51	53 [illegible]	44 [illegible]	·512		·117	8·5
·52	54 [illegible]	45 [illegible]	·490		·095	10·5
·53	56 1[illegible]	47 [illegible]	·461		·066	15·1
·54	56 [illegible]	47 [illegible]	·455		·060	16·6
·55	55	46	·481		·086	11·6
	56	47	·465		·070	14·2
·56	57	48	·447		·052	19·2
·57	57 1[illegible]	48 15	·442		·047	21·2
·58	57 [illegible]	48 [illegible]	·438		·043	23·2
·59	57 [illegible]	48 5[illegible]	·432		·037	27·
·60	57 [illegible]	48 [illegible]	·431		·036	27·7
·61	58 1[illegible]	49 [illegible]	·426		·031	32·2
·62	58 [illegible]	49 [illegible]	·423		·028	35·7
·63	57 [illegible]	48 [illegible]	·438		·033	30·3
·64	57	48	·447		·052	19·2
·65	56	47	·465		·070	14·2
·66	56	47	·465		·070	14·2
·67	56	47	·465		·070	14·2
·68	54	45	·499		·104	9·6
·69	52	43	·534		·139	7·1

TABLE III.

λ	Scale Reading	α	Cos²α	Cos²β	Cos²α − Cos²β	Sensibility
·42μ	70° ′	70° ′	·1169	·25	·1331	7·5
·43	69	69	·1281		·1219	8·2
·44	69 30	69 30	·1225		·1275	7·8
·45	70	70	·1169		·1331	7·5
·46	70 3[illegible]	70 3[illegible]	·1108		·1392	7·1
·47	70 1[illegible]	70 1[illegible]	·1149		·1351	7·4
·48	68 15	68 15	·1369		·1131	8·8
·49	67 30	67 30	·1459		·1041	9·6
·50	66	66	·1648		·0852	11·76
·51	65	65	·1780		·0720	13·8
·52	65	65	·1780		·0720	13·8
·53	66 30	66 30	·1584		·0916	10·9
·54	67 15	67 15	·1489		·1011	9·89
·55	67	67	·1521		·0979	10·21
·56	66	66	·1648		·0852	11·73
·57	65	65	·1780		·0720	13·88

TABLE III.—*Continued.*

λ	Scale Reading	a	Cos^2a	Cos$^2\beta$	Cos^2a — Cos$^2\beta$	Sensibility
·58	64	64	·1918		·0582	17·18
·59	63 ^{30}	63 ^{30}	·1989		·0511	19·56
·60	63	63	·2052		·0448	22·32
·61	62 ^{45}	62 ^{45}	·2088		·0412	24·27
·62	62 ^{15}	62 ^{15}	·2162		·0338	29·58
·63	62 ^{5}	62 ^{5}	·2190		·0310	32·25
·64	61 ^{50}	61 ^{50}	·2227		·0273	36·63
·65	62 ^{50}	62 ^{50}	·2079		·0421	23·75
·66	64	64	·1918		·0582	17·18
·67	64 ^{35}	64 ^{35}	·1840		·0660	15·15
·68	64	64	·1918		·0582	17·18
·69	65	65	·1780		·0720	13·88
·70	67	67	·1521		·0979	10·21
·71	69	69	·1281		·1219	8·2
·72	71	71	·1056		·1444	6·9

TABLE IV.

λ	Scale Reading	a	Cos^2a	Cos$^2\beta$	Cos^2a– Cos$^2\beta$	Sensibility
·45	81° $^{\prime}$	71° $^{45'}$	·097	·060	·037	27
·46	82	72 ^{45}	·087		·027	37
·47	81 ^{50}	72 ^{35}	·089		·029	34·4
·48	81 ^{15}	72	·095		·035	28·5
·49	81 ^{45}	72 ^{30}	·090		·030	33·3
·50	82	72 ^{45}	·087		·027	37·
·51	82 ^{10}	72 ^{55}	·086		·026	38·
·52	82 ^{15}	73	·085		·025	40·
·53	82 ^{20}	73 ^{5}	·084		·024	41·6
·54	82 ^{25}	73 ^{10}	·083		·023	43·4
·55	82 ^{30}	73 ^{15}	·082		·022	44·9
·56	82 ^{35}	73 ^{20}	·081		·021	47·6
·57	82 ^{45}	73 ^{30}	·080		·020	50·
·58	82 ^{50}	73 ^{35}	·079		·019	52·6
·59	82 ^{40}	73 ^{25}	·081		·021	47·6
·60	82 ^{30}	73 ^{15}	·083		·023	43·4
·61	82 ^{40}	73 ^{25}	·081		·021	47·6
·62	82 ^{50}	73 ^{35}	·079		·019	52·6
·63	83	73 ^{45}	·077		·017	58·8
·64	83 ^{20}	74 ^{5}	·075		·015	66·6
·65	83	73 ^{45}	·077		·017	58·8
·66	82 ^{45}	73 ^{30}	·080		·020	50·
·67	82 ^{50}	73 ^{35}	·079		·019	52·6
·68	83	73	·077		·017	58·8
·69	82	72 ^{45}	·087		·027	37
·70	81 ^{30}	72 ^{15}	·092		·032	1·2 3

TABLE V.

λ	Scale Reading	α	$\text{Cos}^2\alpha$	$\text{Cos}^2\beta$	$\text{Cos}^2\alpha - \text{Cos}^2\beta$	Sensibility
·45μ	86° ′	76° 45′	·052	·025	027	37
·46	86 45	77 30	·046		021	47
·47	87	77 45	·044		·019	52
·48	86 30	77 15	·048		023	43
·49	87	77 45	·044		·019	52
·50	87 15	78	·043		·018	55
·51	87 25	78 10	·042		017	58
·52	87 30	78 15	·041		016	62
·53	87 40	78 25	·040		015	66
·54	87 55	78 40	·038		·013	76
·55	88	78 45	·038		·012	83
·56	88 10	78 55	·036		011	90
·57	88 5	78 50	·037		011	90
·58	88	78 45	·038		012	83
·59	87 55	78 40	·038		·013	76
·60	88 5	78 50	·037		·011	94
·61	88 15	79	·036		·010	100
·62	88 25	79 10	035		·009	111
·63	88 30	79 15	·034		·008	125
·64	88 10	78 55	·136		·011	94
·65	87 50	78 35	·038		·012	83
·66	87 30	78 15	·041		·016	62
·67	87 5	77 50	·044		·019	52
·68	87 25	78 10	·042		·017	58
·69	88	78 45	·038		·013	76
·70	87 30	78 15	·041		·016	62
·71	83	73 45	·077		·052	19

TABLE VI.

λ	Scale Reading	α	$\text{Cos}^2\alpha$	$\text{Cos}^2\beta$	$\text{Cos}^2\alpha - \text{Cos}^2\beta$	Sensibility
	° ′	° ′				
·45	93	83 45	·0116	·0054	·0062	16·1
·46	93 45	84 30	·0090		·0036	27·7
·47	93 30	84 15	·0100		·0046	21·7
·48	93	83 45	·0116		0062	16·1
·49	93 15	84	·0108		0054	18.5
·50	93 20	84 5	.0106		·0052	19·2
·51	93 30	84 15	·0100		·0046	21·7
·52	93 35	84 20	·0096		0042	23·8
·53	93 40	84 25	·0094		·0040	25
·54	93 45	84 30	·0090		0036	27·7
·55	93 50	84 35	·0088		0034	29·4
·56	93 55	84 40	·0084		0030	33·3
·57	93 60	84 35	·0088		0034	29·4
·58	93 45	84 30	·0090		0036	27·7
·59	93 50	84 35	·0088		0034	29·4
·60	93 55	84 40	·0084		·0030	33·3
·61	94	84 45	·0082		·0028	35·7
·62	94 5	84 50	·0081		0027	37·0
·63	94 10	84 55	·0077		·0023	43·4
·64	94	84 45	·0082		·0028	35·7
·65	93 40	84 25	·0094		·0040	25·
·66	93 30	84 15	·0100		·0045	21·7
·67	93 15	84	·0108		·0054	18·5
·68	93 45	84 30	·0090		0036	27·7
·69	92	82 45	·0158		·0104	9·6
·70	89	79 45	·0313		·0259	3·8

TABLE VII.

Least perceptible increment as observed upon light of varying intensity and of wave length=$\cdot 42\mu$.

Scale Reading		a		Cos^2a	Least percep'ble Increment	Sensibility
°	'	°	'			
99		90			·0210	47
90	30	81	30	·0210	·0121	82
88	30	79	30	·0331	·0249	40
85		76		·0580	·0374	26
81		72		·0954	·0567	17
76		67		·1521	·1131	8
68		59		·2652	·1823	5
57		48		·4475	·2716	3
41		32		·7191	·2809	3
9		0		1·0000		

TABLE VIII.

Least perceptible increment as observed upon light of varying intensity and of wave length=45μ.

Scale Reading		a		Cos^2a	Least percep'ble Increment	Sensibility
°	'	°	'			
99		90		·0	·0004	2500
97	45	88	45	·0004	·0008	1250
97		88		·0012	·0013	769
96	5	87	5	·0025	·0029	344
94	45	85	45	·0054	·0055	181
93		84		·0109	·0122	81·9
90	15	81	15	·0231	·0166	60·2
87	30	78	30	·0397	·0188	53·1
85		76		·0585	·0260	38·4
82	5	73	5	·0845	·0324	30·8
79		70		·1169	·0369	27·
75	55	66	55	·1538	·0364	27·
73	5	64	5	·1902	·0448	22·3
70		61		·2350	·0457	21·8
67		58		·2807	·0983	10·1
61		52		·3790	·1559	6·4
52	15	43		·5349	·2150	4·6
39		30		·7499	·2391	4·1
15		6		·9890		

TABLE IX.

Least perceptible decrement as observed upon light of varying intensity and of wave length = ·45μ

Scale Reading		a		Cos²a	Least perceptible Decrement	Sensibility
°	′	°	′			
0		0		1·	·1530	
23		23		·8470	·2665	3·8
40		40		·5867	·1992	5
51	30	51	30	·3875	·1562	6·4
61	15	61	15	·2313	·1144	8·5
70		70		·1169	·0663	15·
77		77		·0506	·0313	31·
82		82		·0193	·0117	85·
85		85		·0076	·0043	232·
86	40	86	40	·0033	·0011	909·
87	15	87	15	·0022	·0007	1428·
87	45	87	45	·0015	·0005	2000·
88	10	88	10	·0010	·0005	2000·
88	40	88	40	·0005	·0003	3333·
89	10	89	10	·0002	·0002	5000·
90		90		·0		

TABLE X.

Least perceptible increment as observed upon light of varying intensity and of wave length—.52 μ.

Scale Reading		a		Cos²a	Least perceptible Increment	Sensibility
°	′	°	′			
90		90		·0	·0001	10000.
89	30	89	30	·0001	·0003	3333·
89		89		·0004	·0004	2500
88	30	88	30	·0008	·0004	2500
88		88		·0012	·0008	1250
87	30	87	30	·0020	·0008	1250
87		87		·0028	·0010	1000
86	30	86	30	·0038	·0010	1000
86		86		·0048	·0013	769
85	30	85	30	·0061	·0015	666
85		85		·0076	·0016	625
84	30	84	30	·0092	·0022	454
83	45	83	45	·0114	·0036	277
83		83		·0150	·0069	145
81	45	81	45	·0219	·0054	185
80	30	80	30	·0273	·0123	81
78	30	78	30	·0396	·0085	117
77	15	77	15	·0481	·0169	59
75	10	75	10	·0650	·0125	80
73	45	73	45	·0775	·0233	42
71	30	71	30	·1008	·0237	42
69	15	69	15	·1245	·0282	36
67		67		·1527	·0327	30
64	30	64	30	·1854	·0300	33
62	15	62	15	·2154	·0347	28
60		60		·2501	·0790	12·6
55		55		·3291	·0842	11·9
50		50		·4133	·0955	10·4
44	30	44	30	·5088	·1457	6·8
36		36		·6545	·1796	5·6
24		24		·8341	·1358	7·3
10		10		·9699		

TABLE XI.

Least perceptible decrement as observed upon light of varying intensity and of wave length $= \cdot 52\mu$.

Scale Reading		a		$\text{Cos}^2 a$	Least perceptible decrement	Sensibility
°	′	°	′			
39		29		·763	·160	6·25
49		39		·603	·122	8·2
56		46		·481	·112	8·9
62	30	52	30	·369	·074	13·5
67		57		·295	·053	18·8
70	30	60	30	·242	·043	23·2
73	30	63	30	·198	·038	26·3
76	25	66	25	·160	·026	38·4
78	28	68	28	·134	·018	55·5
80	8	70		·116	·021	47·6
82		72		·095	·015	66·6
83	30	73	30	·080	·013	76·9
84	55	74	55	·067	·010	100
86	5	76	5	·057	·015	66·6
88		78		·042	·012	83·3
89	55	79	55	·030	·007	142·8
91	15	81	5	·023	·008	125·
92	45	82	45	·015	·003	333·
93	30	83	30	·012	·002	500·
94	10	84	10	·010	·004	225·
95	30	85	30	·006	·003	333·
96	50	86	50	·003	·001	1000·
97	15	87	15	·002		

TABLE XII.

Least perceptible increment as observed upon light of varying intensity and of wave length $= \cdot 57\mu$.

Scale Reading		a		$\text{Cos}^2 a$	Least perc'ble Increment	Sensibility
°	′	°	′			
90		90				
97	45	88	45	·0004		
97	29	88	29	·0007	·0004	2500·
97	2	88	2	·0011	·0006	1666·6
96	35	87	35	·0017	·0008	1250·
96	5	87	5	·0025	·0011	909
95	33	86	33	·0036	·0012	833
95		86		·0048	·0015	714
94	26	85	26	·0063	·0017	588
93	51	84	51	·0080	·0020	526
93	13	84	13	·0100	·0032	312
92	23	83	23	·0132	·0037	270
91	30	82	30	·0169	·0047	213
90	32	81	32	·0216	·0056	178
89	30	80	30	·0272	·0070	142
88	20	78	20	·0342	·0082	122
87	6	78	6	·0424	·0091	109
85	50	76	50	·0515	·0110	90

TALBE XII.—*Continued*

Least perceptible increment as observed upon light of varying intensity and of wave length = ·57*μ*.

Scale Reading		*a*		Cos *a*	Least perceptible Increment	Sensibility
84	30	75	30	·0625	0125	80
83	5	74	5	·0750	0150	66
81	32	72	[illegible]	·0900	0162	61
79	[illegible]	70	[illegible]	·1062	0191	52
78	15	69	15	·1256	0229	43·6
76	25	67	25	·1482	0265	37·7
71	15	65	15	·1747	0305	32·7
72		63		·2052	0358	27·9
69	[illegible]	60	35	·2410	0420	23·8
66	50	57	[illegible]	·2830	0499	20
63	45	54	45	·3329	0665	15
59	45	50	45	·3994	0698	14·3
55	45	46	45	·4692	0903	11
50	30	41	[illegible]	·5595	·1277	7·8
43		34		·6872	·1463	6·8
33		24		·8335	1446	6·9
17	30	8	[illegible]	·9781		

TABLE XIII.

Least perceptible increment as observed upon light of varying intensity and of wave length = ·63*μ*.

Scale Reading		*a*		Cos *a*	Least Perceptible Increment	Sensibility
°	′	°	′			
97	15	88	15	·0009	0006	1666·
96	45	87	45	·0015	0012	833
96		87		·0027	0016	625
95	10	86	10	·0043	0029	344
94	5	85	5	·0072	0057	175
92	25	83	25	·0129	0058	172
91	5	82	5	·0187	0108	92
89	5	80	5	·0295	0089	112
87	40	78	40	·0384	0113	88
86	5	77	5	·0497	0083	120
85		76		·0580	0132	75
83	10	74		·0712	0164	60
81	45	72	45	·0876	0173	57
80	5	71	5	·1049	0225	44
78	5	69	5	·1274	0154	64
76	45	67	45	·1428	0220	45
75		66		·1618	0270	37
73		64		·1918	0281	35
71		62		·2199	0301	33
69		60		·2500	0459	21
66		57		·2959	0405	24
63	[illegible]	54	[illegible]	·3364	0504	19
60	[illegible]	61	[illegible]	·3868	0742	13
56	[illegible]	47	[illegible]	·4610	0559	17
53		44		·5169	0775	12
48	[illegible]	39	[illegible]	·5944	0845	11
45	[illegible]	34	[illegible]	·6789	0814	12
38	15	29	[illegible]	·7603	0732	13
33		24		·8335	·0900	11
25		16		·9235		

TABLE XIV.

Least perceptible increment as observed upon light of varying intensity and of wave length=·69μ.

Scale Reading		a		$\text{Cos}^2 a$	Least percept'ble Increment	Sensibility
°	′	°	′			
99		90		·0	·0169	59·1
91	30	82	30	·0169	·0130	76·9
89		80		·0299	·0225	44·4
85	45	76	45	·0524	·0376	26·5
81	30	72	30	·0900	·0439	22·7
77	30	68	30	·1339	·0579	17·2
73		64		·1918	·0652	15·3
68	30	59	30	·2570	·0794	12·5
63	30	54	30	·3364	·1111	9
57		48		·4475	·1392	7·2
48		40		·5867	·1771	5·6
38		29		·7638	·1848	5·4
22		13		·9486		

TABLE XV.

λ	β		α		Cos²α	Cos²β	Least Percep'le Increment	Luminosity	Inc. Cos² β	Sensibility	Di I+Di
	°	′	°	′							
·460μ	35		22		·8593	·6711	·1882	5·3	·28	3·56	·22
·480	63		57		·2959	·2060	·0899	11·1	·43	2·29	·30
·491	70		64	30	·1819	·1170	·0679	14·7	·58	1·72	·36
·500	76	45	73	18	·0826	·0525	·0301	33·2	·57	1·75	·36
·515	83		80	30	·0272	·0148	·0124	80·6	·83	1·20	·45
·530	84	54	83	15	·0138	·0079	·0059	169·5	·74	1·35	·42
·564	87		85	45	·0052	·0033	·0019	526·3	·58	1·72	·36
·593	87	42	87		·0027	·0016	·0011	909·0	·68	1·47	·40
·601	87	42	87		·0027	·0016	·0011	909·0	·68	1·47	·40
·621	87	15	86	25	·0038	·0023	·0015	666·6	·65	1·54	·39
·648	86		85		·0076	·0048	·0028	357·1	·58	1·72	·36
·663	84		82	15	·0179	·0109	·0070	142·8	·64	1·56	·39
·677	79		75		·0665	·0364	·0301	33·2	·82	1·22	·45
·695	73	24	68	30	·1339	·0816	·0523	19·1	·64	1·56	·39
·712	55	24	45	30	·4900	·3224	·1676	5·9	·52	1·92	·39
·733	37	20	17		·9139	·6295	·2844	3·5	·45	2·22	·31

From the PHILOSOPHICAL MAGAZINE, vol. xxxviii. *July* 1919.

The Persistence of Vision of Colours of Varying Intensity.

By FRANK ALLEN, *Ph.D., F.R.S.C., Professor of Physics, University of Manitoba, Canada.*

IN a former communication to the Philosophical Magazine* a method of measuring the luminosity of the spectrum was discussed, which may also be used for the determination of the persistence of vision of colours of varying intensity. The arrangement of apparatus employed in the present investigation is very similar to that described in the paper referred to, and is shown diagrammatically in fig. 1.

Light from the acetylene flame (A), after concentration by a lens (B), passed through an open sector (90°) of the disk (C) which was rotated by an electric motor, then through two Nicol prisms (D and E) arranged with their principal

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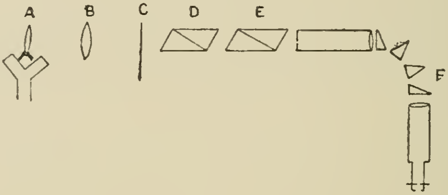
[*] "A New Method of Measuring the Luminosity of the Spectrum," May 1911.

sections horizontal, thence through the spectrometer (F), and was finally viewed in an eyepiece in which all the light of the spectrum, except a narrow central band of any desired colour, was cut off by means of adjustable shutters.

Fig. 1.



In making the measurements, the eye, which before each reading was always rested in ordinary daylight, observed any selected patch of colour which was caused to flicker by the rotation of the sectored disk. The speed of the disk was increased until the critical frequency of flicker was reached, and then electrically recorded on a chronograph.

At first the principal sections of the nicols were parallel, so that a persistency curve might be obtained for the greatest intensity of light possible with the apparatus. It may be pointed out that any error arising from the use of Nicol prisms in colour measurements does not affect these results, as they are purely comparative.

On subsequent days similar curves were obtained for spectra whose intensities were diminished in determinate amounts by rotating the polarizer through suitable angles. In all, nine curves were determined for a series of luminosities varying from the fullest brightness of the spectrum down to the point where very little light was perceptible.

In Table I. the first column shows the wave-lengths for which determinations of the duration of the luminous impression at the critical frequency of flicker were made, viz. $\lambda \cdot 725\,\mu$, $\lambda \cdot 665\,\mu$, $\lambda \cdot 590\,\mu$, $\lambda \cdot 520\,\mu$, $\lambda \cdot 460\,\mu$, and $\lambda \cdot 430\,\mu$; the other wave-lengths in the table, and the corresponding data, were obtained by inspection from the curves formed by the first six experimental values. The non-experimental data are placed in the table to indicate the lowest points on the respective persistency curves, and hence denote the brightest points in the corresponding spectra. The numbers, 0°, 20°, 40°, &c., at the heads of the pairs of columns in the table, are the angles between the principal sections of the nicols from which the relative brightnesses of the corresponding spectra are computed.

TABLE I.

Persistence of Vision and Luminosity.

	0°.		20°.		40°.		60°.	
λ	D	L	D	L	D	L	D	L
·725 μ	·0286 sec.	11·7	·0290 sec.	11·3	·0312 sec.	9·6	·0366 sec.	6·8
·665	·0184	46·1	·0187	[illegible]	·0203	[illegible]	·0221	24·2
·590	·0153	100·0	·0155	94·5	·0162	77·0	·0178	52·7
·520	·0169	61·6	·0172	[illegible]	·0182	48·0	·0202	32·8
·460	·0254	16·0	·0261	14·9	·0279	12·4	·0317	9·2
·430	·0448	4·9	·0464	4·7	·0507	4·0	·0622	3·1

	70°.		80°.		85°.		87° 18′.	
λ	D	L	D	L	D	L	D	L
·725 μ	·0436 sec.	5·1	·0603 sec.	3·3				
·665	·0251	16·6	·0321	8·7	·0454 sec.	4·8	·0625 sec.	3·0
·590	·0196	36·5	·0258	19·2	·0303	10·3	·0366	6·8
·520	·0224	23·2	·0268	13·9	·0340	7·9	·0415	5·5
·460	·0359	7·2	·0476	4·4	·0684	2·8	·0795	2·45
·430	·0805	2·5	·0980	2·1	·0856	2·2	...	...
·585	·0194	37·9	...	...	...	...	...	...
·583	...	...	·0232	20·7	...	...	...	...
·575	...	...	...	...	·0300	10·4	...	...
·572	...	...	...	...	...	...	·0360	7·1

	88° 12′.		88° 30′.	
λ	D	L	D	L
·725 μ	...	...	...	...
·665	·0820 sec.	2·4	...	...
·590	·0397	5·9	·0434 sec.	5·1
·520	·0467	4·6	...	...
·570	·0391	6·1	...	...

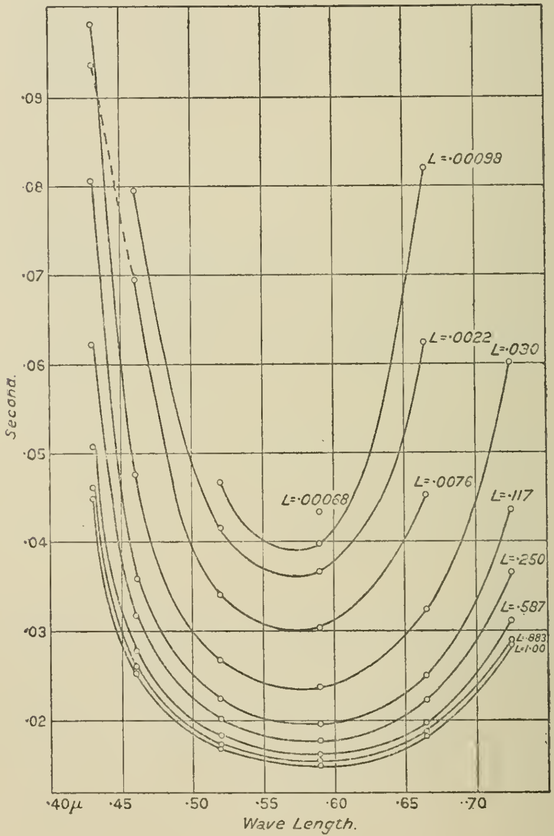
In the columns under D are the values of the persistence of vision, or the duration of the visual impressions. In the columns under L are the luminosities corresponding to the values of D. These are obtained by assuming a luminosity of 100 for the smallest value of D, 0·0153 sec., in the whole table, and then applying the Ferry-Porter law in its simple form

$$D = \frac{1}{k \log L}$$

for the other values of D in all the columns.

In fig. 2 the values of D and the wave-lengths are used as coordinates, which give a series of nine persistency curves for intensities varying almost to invisibility. The curve for the brightest spectrum corresponding to the angle 0° between the sections of the nicols is at the bottom of the figure, and that for the dimmest spectrum at the top. In the "curve" for 88° 30′ only one point was obtained. It will be noticed that the brightest points of the spectra, represented by the lowest values in the curves, gradually shift from the yellow towards the blue as the spectral intensities grow smaller.

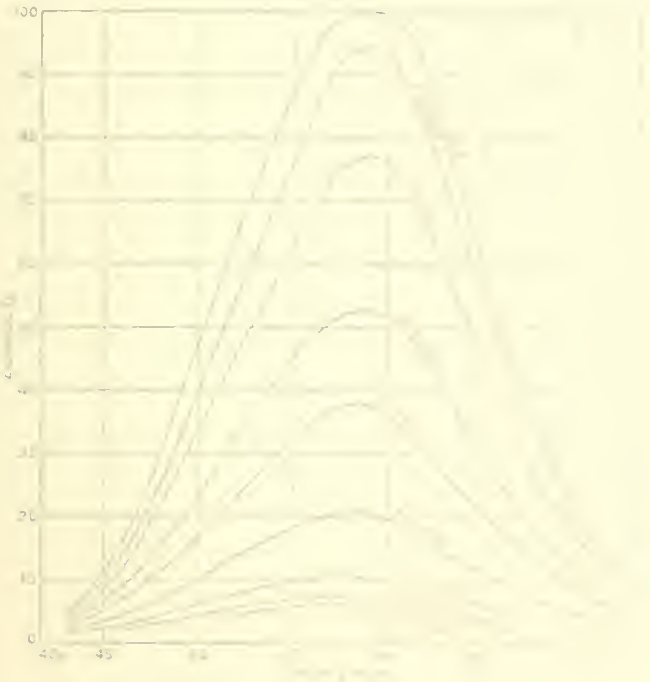
Fig. 2.



The displacement of the brightest point here indicated is not so great as other observers have obtained by different methods.

In fig. 3 the coordinates are the values of the luminosity, L, and the wave-lengths in Table I. These give a corresponding series of luminosity curves for spectra of diminishing intensities, the brightest spectrum being represented by the highest curve. These are of the usual type of luminosity curves, and also show the displacement of the brightest point of the spectrum towards the blue when the intensities are diminished. There is a marked flattening of the curves as they approach the lowest, which is that for the dimmest spectrum.

Fig. 5.



A somewhat similar group of three luminosity curves was obtained by Haycraft* by the flicker method, who, however, employed colour disks at three different intensities of illumination instead of spectral colours. His curves are somewhat the same as those in fig. 5, but are noticeable for a much greater displacement towards the blue of the brightest point than is indicated in my own curves.

In Table II. the first column shows the angles, α, between the principal sections of the nicols, the second the values of $\cos^2 \alpha$ to which the luminosities are proportional, and the remaining columns in pairs under the wave-lengths, $\lambda \cdot 725\,\mu$, &c., show the values of the persistency of vision, P, and their reciprocals.

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* Journ. of Physiol. vol. xxi. (1897).

Table II.

Curves for Diminishing Intensity of Spectrum.

Angle between Pol. and Anal.	$l=\cos^2 \alpha$.	$\lambda = \cdot 725\,\mu$.		$\lambda = \cdot 665\,\mu$.		$\lambda = \cdot 590\,\mu$.	
α.	$\cos^2 \alpha$.	D	$\frac{1}{D}$	D	$\frac{1}{D}$	D	$\frac{1}{D}$
0°	1·000	·0286 sec.	34·96	·0184 sec.	54·35	·0153 sec.	65·36
20°	0·883	·0290	34·48	·0187	53·48	·0155	64·52
40°	·587	·0312	32·05	·0198	50·50	·0162	61·73
60°	·250	·0366	27·32	·0224	44·64	·0178	56·18
70°	·117	·0436	22·93	·0251	39·84	·0196	51·02
80°	·030	·0603	16·58	·0324	30·86	·0238	42·02
85°	·0076	......	......	·0454	22·03	·0303	33·03
87° 18′	·0022	......	......	·0625	16·00	·0366	27·32
88° 12′	·00098	......	......	·0820	12·19	·0397	25·19
88° 30′	·00068	......	......	......	......	·0434	23·04

		$\lambda = \cdot 520\,\mu$.		$\lambda = \cdot 460\,\mu$.		$\lambda = \cdot 430\,\mu$.	
α.	$\cos^2 \alpha$.	D	$\frac{1}{D}$	D	$\frac{1}{D}$	D	$\frac{1}{D}$
0°	1·000	·0169 sec.	59·17	·0254 sec.	39·37	·0448 sec.	22·32
20°	0·883	·0172	57·55	·0261	38·31	·0461	21·69
40°	·587	·0182	54·39	·0279	35·84	·0507	19·72
60°	·250	·0202	49·50	·0317	31·55	·0622	16·08
70°	·117	·0224	44·64	·0359	27·86	·0805	12·42
80°	·030	·0268	37·31	·0476	21·00	·0980	10·20
85°	·0076	·0340	29·41	·0694	14·41	·0936	10·68
87° 18′	·0022	·0415	24·09	·0795	12·58	......	......
88° 12′	·00098	·0467	21·41	......	......	......	......
88° 30′	·00068	.....	......	......	......	......	......

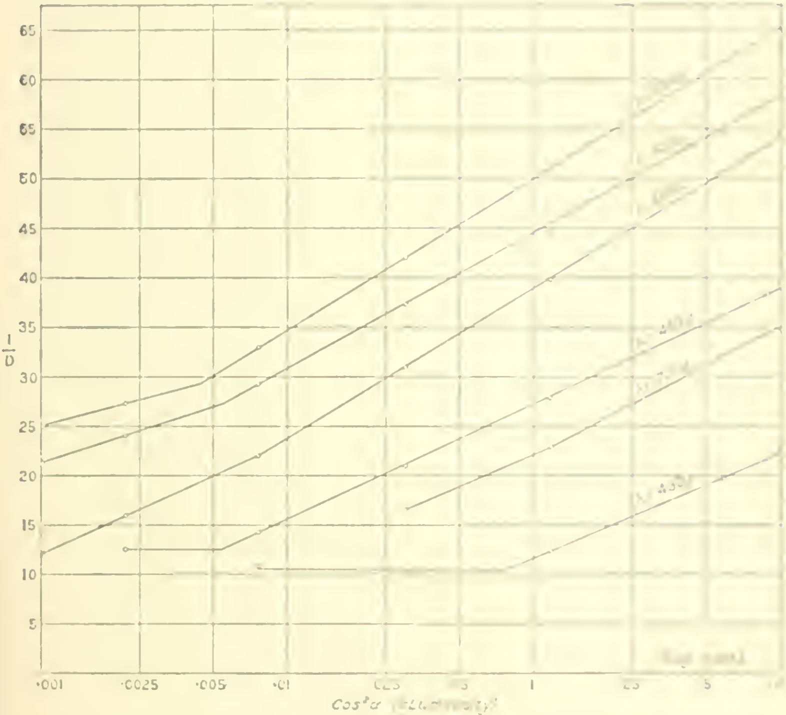
From the Ferry-Porter law we have the relation

$$\frac{1}{D} = k \log L + k'.$$

By plotting the values of $\frac{1}{D}$ and $\cos^2 \alpha$ on semilogarithmic paper, there results a group of straight lines which are shown in fig. 4. Each curve of the six in the figure represents a series of diminishing values of intensities for a single portion of the spectrum, the centre of which has the wave-length indicated on the curve. Each curve also is composed of two straight lines. The change of direction appears to be very abrupt, though probably the sharpness would give place to a somewhat more gradual change if a series of observations were to be made for slight alterations in brightness.

On comparing the curves it will be noticed that the upper portions of all fall into two groups. Those in the red orange, and yellow, for the wave-lengths $\lambda\ \cdot 725\,\mu$, $\lambda\ \cdot 665\,\mu$, and $\lambda\ \cdot 590\,\mu$, approach parallelism, the last two being almost exactly so. The remaining curves for green, blue, and violet, λ·520 μ, λ·460 μ, and λ·430 μ, show somewhat the same characteristic relation.

Fig. 4.



The lower portions of all the curves show the most striking differences. Those for λ·665 μ and λ·725 μ are not far from being continuous in direction with the upper portions of the curves, while those for λ·460 μ and λ·430 μ are quite horizontal. The others lie at various inclinations between these two extremes. Though in the curve for λ·460 μ there is but one point in the lower part, yet I have made that portion horizontal since Ives obtained this result for the longer wavelength λ·48 μ and I for λ·430 μ.

These curves confirm similar results previously obtained by Porter* and by Ives†. Porter's results were for a disk with white-light illumination, while those of Ives were for five spectral colours. The latter found the curve for λ·65 μ to be exactly a straight line. Considering the curves of Ives and my own, it would appear that the lower portions of the curves for λ·480 μ, λ·460 μ, and λ·430 μ are all nearly horizontal, though probably only one is exactly so. My curve for λ·430 μ shows a slight upward tilt of the lower part, though the data are too scanty to give a reliable conclusion.

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* Proc. Roy. Soc. lxx. p. 313 (1902).

† Phil. Mag. xxiv. p. 352 (1912).

In regard to the meaning of the abrupt change of direction shown by the curves, there is probably no reason to question the interpretation based on the duplicity theory of von Kries*, that the upper part relates to vision by the retinal cones, the lower part by the rods, and the sharp change in direction marks the sudden transition from the one to the other.

It is evident from the curves that the critical frequency of flicker, or persistence of vision, is not simply dependent on the luminosity alone, but that colours *per se* have peculiar and independent effects of their own †.

In those curves which have a portion horizontal it appears that the effect of the diminishing intensity of the light is just balanced by some restraining influence of the colour.

The Purkinje phenomenon, or the displacement of the brightest point of the spectrum towards the blue when the intensity of the light is diminished, has been shown by the curves in the preceding figures. The tables, however, contain data which can be used to exhibit this important phenomenon in a more specific manner. For each value of $\cos^2 \alpha$ there is a series of relative values of the luminosity, L, for the various spectral lines studied. Taking the red of λ·665 μ as a standard of reference, and plotting its luminosities horizontally, the corresponding values of L for the green of λ·520 μ, the blue of λ·460 μ, and the violet of λ·430 μ, can be plotted as ordinates so as to give curves of equivalent luminosities. If the luminosities of these colours rise or fall at the same rate, the resulting curves ought to be straight lines. The data from the preceding tables are arranged in Table III., and are displayed graphically in fig. 5.

The three curves in the figure alike show the relative increase in brightness of the green, blue, and violet lights compared with the red, since they deviate from straight lines at the lower intensities. As the violet is approached it is to be expected that the phenomenon should manifest itself over an increasing portion of the curve, as it does in the figure. This confirms and extends similar results obtained by König*.

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* 'Colour Vision,' J. H. Parsons, p. 208.

† *Ibid.*, p. 98.

Fig. 5.

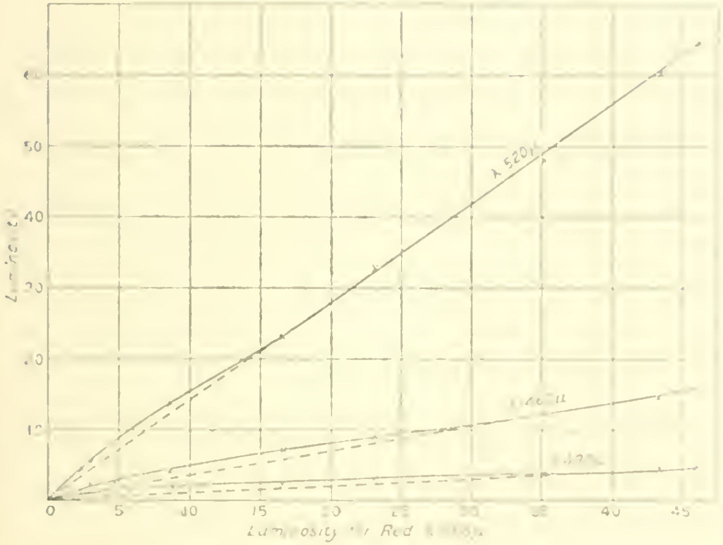

TABLE III.

cos² α.	Red λ 665 μ. L.	Green λ·520 μ. L.	Blue λ·460 μ. L.	Violet λ·430 μ. L.
1·000	46·1	64·6	16·0	4·9
·883	43·3	60·3	14·9	4·7
·587	35·1	48·0	12·4	4·0
·250	23·2	32·8	9·2	3·1
·117	16·6	23·2	7·2	2·5
·030	8·7	13·9	4·4	2·4
·0076	4·8	7·9	2·8	2·2
·0022	3·0	5·5	2·45	
·00098	2·4	4·6	1·5	

My original intention was only to obtain the curves for the persistence of vision which are shown in fig. 1. Consideration of the data obtained, however, showed that they could be utilized in the various ways discussed in this paper. These are largely the confirmation, as well as the extension, of the work of other investigators, which is always desirable, especially when different methods of experimentation are used. This confirmation has an additional advantage, since it shows how completely reliable is the method of the critical frequency of flicker, or persistence of vision, as a means of investigating the phenomena of colour vision.

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* König, *Gesammelte Abhandlungen*, p. 144; also 'Colour Vision,' Parsons, p. 59.

From the PHILOSOPHICAL MAGAZINE, vol. xxxviii. *July* 1919.

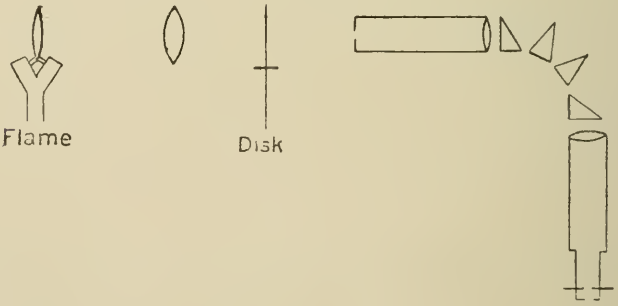
On the Discovery of Four Transition Points in the Spectrum and the Primary Colour Sensations. By FRANK ALLEN, *Ph.D., F.R.S.C., Professor of Physics, University of Manitoba, Winnipeg.*

THE researches in colour-vision which I have made from time to time have had for their secondary object the extension of our knowledge of the persistence of vision, and for their primary object the determination in an incontrovertible manner, if possible, of the number of fundamental colour-sensations, and the precise waves of light by which they are excited, concerning which there has been and still is much controversy.

In this communication I have gathered together some results previously published, and incorporated with them new investigations which appear absolutely to determine the number of the fundamental colour-sensations. With the method of study which I have used it does not yet seem possible to designate the exact waves of light which excite the primary sensations of colour; but it is possible to determine the limits between which these hues must lie.

The apparatus used for purposes of measurement was similar to that described in a former paper*, and essentially the same as that devised and used by E. L. Nichols†. Light from an acetylene flame passed through a disk with two opposite open sectors of ninety degrees each, whose speed of rotation was electrically recorded upon a chronograph. The flickering light was dispersed into a spectrum by a suitable spectrometer, and a shutter eyepiece enabled observations to be made as desired upon narrow strips of the spectrum. The speed of the disk was adjusted so that the flickering of the light became just imperceptible and then recorded. The arrangement is shown by the diagram in fig. 1.

Fig. 1.



By means of an arc-light and a second spectrometer with two prisms, a brilliant spectrum of considerable dispersion was formed, narrow portions of which were isolated by a shutter eyepiece, and used to fatigue the eye with which observations of the persistence of vision were made. An interval of time of about three minutes was allowed for fatiguing the eye before each measurement of the critical time of flicker was made. In this way a persistency curve

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[*] Allen, "Effect on the Persistence of Vision of Exposing the Eye to Light of Various Wave-Lengths," Phys. Rev. xi. 1900.

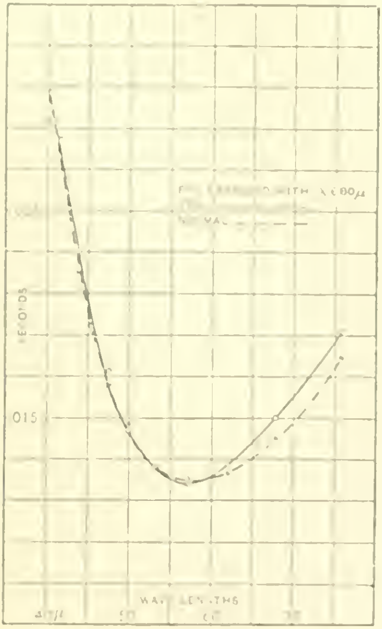
[†] "On the Duration of Colour Impressions on the Retina," Am. Journ. Sci. xxviii. 1884.

for the whole spectrum was obtained which can be compared with a normal curve previously determined when the eye was adapted for diffused daylight. At various times these curves have been obtained, and in this paper seventeen of them are compared and discussed.

In two former investigations* curves were described for seven portions of the spectrum, viz.: for red, orange, yellow, green, blue, and violet, the wave-lengths of which were respectively $\lambda \cdot 680\,\mu$, $\lambda \cdot 620\,\mu$, $\lambda \cdot 589\,\mu$, $\lambda \cdot 577\,\mu$, $\lambda \cdot 520\,\mu$, $\lambda \cdot 440\,\mu$, and $\lambda \cdot 400\,\mu$. These curves are all reproduced in this paper.

In a communication to the British Association† at its Winnipeg meeting, I pointed out a very curious and remarkable effect occurring when the fatiguing colour was $\lambda \cdot 660\,\mu$. It will be noticed from fig. 2 that the persistency

Fig. 2.



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* "Effect on Persistence of Vision, etc.," Phys. Rev. xi. 1900. "Some Phenomena of the Persistence of Vision," Phys. Rev. vol. xxviii. 1909. Also Trans. Roy. Can. 1908.

† Report of B.A.A.S. 1909, p. 4 0.

curve obtained when the eye was fatigued with a pure red of wave-length λ ·680 μ has in it a single characteristic elevation which corresponds to the red portion of the spectrum, the rest of the curve coinciding with the normal. It will also be noticed from fig. 8, that when the fatiguing colour was the wave-length λ ·589 μ, there were two elevations in the curve, one in the red as before, and the second in the part corresponding to green. It occurred to me that there must be in the spectrum a point of transition from the type of curve with one elevation to that with two, and that the curve obtained when this transition point was made the fatiguing colour would probably differ in some way from both. Accordingly, search was made for it. The eye was fatigued with the colour λ ·670 μ, and the readings in Table I. were obtained.

Table I.

λ.	Normal Persistence.	Eye fatigued with λ ·670 μ.	λ.	Normal Persistence.	Eye fatigued with λ ·670 μ.
·733 μ	·0340 sec.	·0380 sec.	·530 μ	·0171 sec.	·0175 sec.
·695	·0248	·0266	·500	·0215	·0224
·663	·0198	·0214	·470	...	·0306
·601	·0156	·0155	·460	·0332	...
·564	·0157	·0155	·430	·0513	...

These values are plotted in fig. 3, and give a curve with one elevation, similar to that for the wave-length λ ·680 μ. Similarly, curves were obtained for the wave-lengths λ ·651 μ and λ ·625 μ, the data for which are tabulated in Table II. and Table III. respectively.

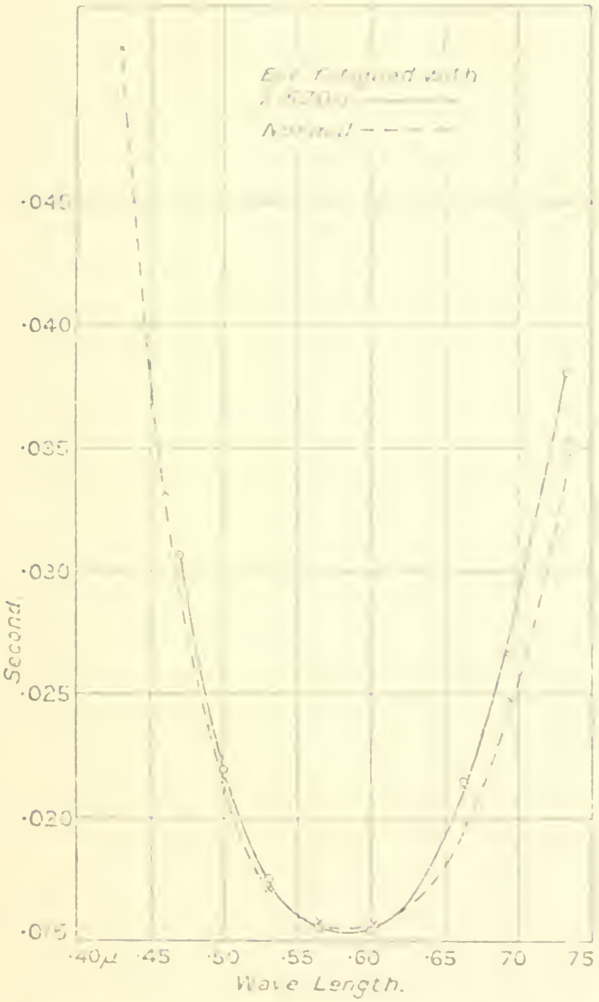
Table II.

λ.	Normal Persistence.	Eye fatigued with λ ·651 μ.	λ.	Normal Persistence.	Eye fatigued with λ ·651 μ.
·733 μ	·0318 sec.	·0353 sec.	·530 μ	...	·0177 sec.
·695	·0232	·0254	·500	·0189 sec.	·0189
·663	·0185	·0197	·460	·0310	...
·601	·0144	·0145	·430	·0458	...
·564	·0147	·0153	...	...	...

Table III.

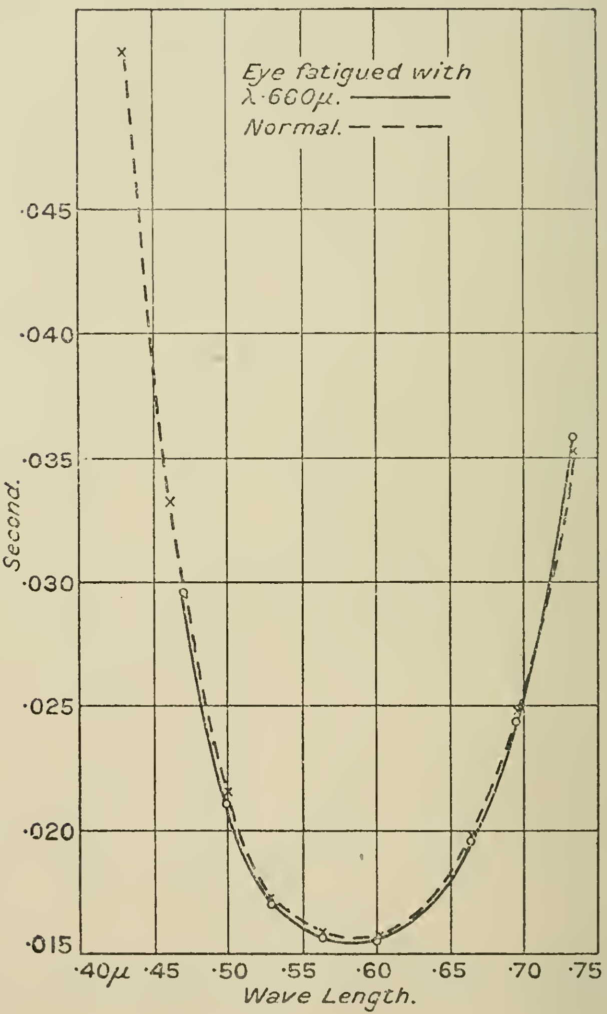
λ.	Normal Persistence.	Eye fatigued with λ·625μ.	λ.	Normal Persistence.	Eye fatigued with λ ·625 μ.
·733 μ	·0318 sec.	·0364 sec.	·530 μ	...	·0170 sec.
·695	·0232	·0249	·500	·0189 sec.	·0194
·663	·0185	·0190	·460	·0310	...
·601	·0144	·0144	·430	·0458	...
·564	·0147	·0162	...	...	...

Fig. 3.



The corresponding curves are shown in fig. 5 and fig. 6. Both are of the same type, and exhibit two elevations similar to those in the curve for the wave-length λ ·589 μ in fig. 8. As these measurements are tedious to make, I yielded to the temptation to determine these curves, and a few others, as will be noticed, only for those parts where experience shows the elevations can occur. There can be no doubt that the rest of the curve would coincide with the normal.

Fig. 4.

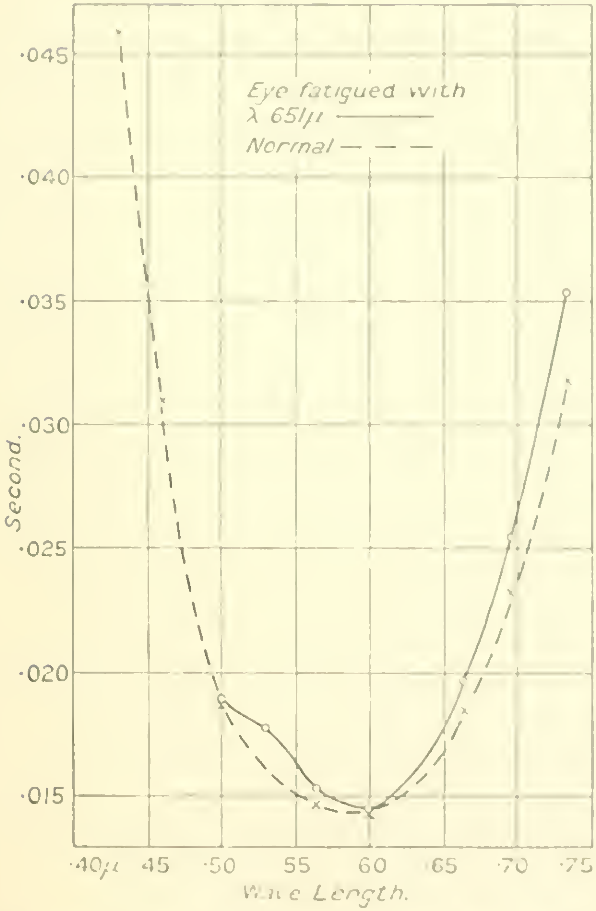


The transition point was thus narrowed down to the wave-length λ·660 μ. The eye, therefore, was fatigued with this colour, and from the data obtained, Table IV., the curve in fig. 4 was plotted.

TABLE IV.

λ.	Normal Persistence	Eye fatigued with λ 651μ	λ.	Normal Persistence	Eye fatigued with λ 651μ.
·735μ	·0318 sec.	·0353 sec.	·530μ	·0172 sec.	·0170 sec.
·696	·0238	·0253	·500	·0215	·0211
·663	·0188	·0196	·470	...	·0265
·601	·0146	·0145	·450	·0352	...
·564	·0147	·0153	·430	·0445	.

Fig. 5.



No elevations at all appeared, and the abnormal curve coincided with the normal throughout their length. This surprising result at first was taken to indicate that the eye had not been sufficiently fatigued or that the readings were not properly taken. With the greatest care the whole of the readings were repeated on the following day with exactly the same result. The remarkable conclusion follows, that fatiguing the eye with a narrow band of colour whose central wave-length is λ ·660 μ, has not the slightest perceptible effect on the measurement of the persistence of vision for any part of the spectrum. This wave-length, λ ·660 μ, is therefore the transition point between curves of the single red elevation type and those of the double red and green elevation type.

Fig. 6.

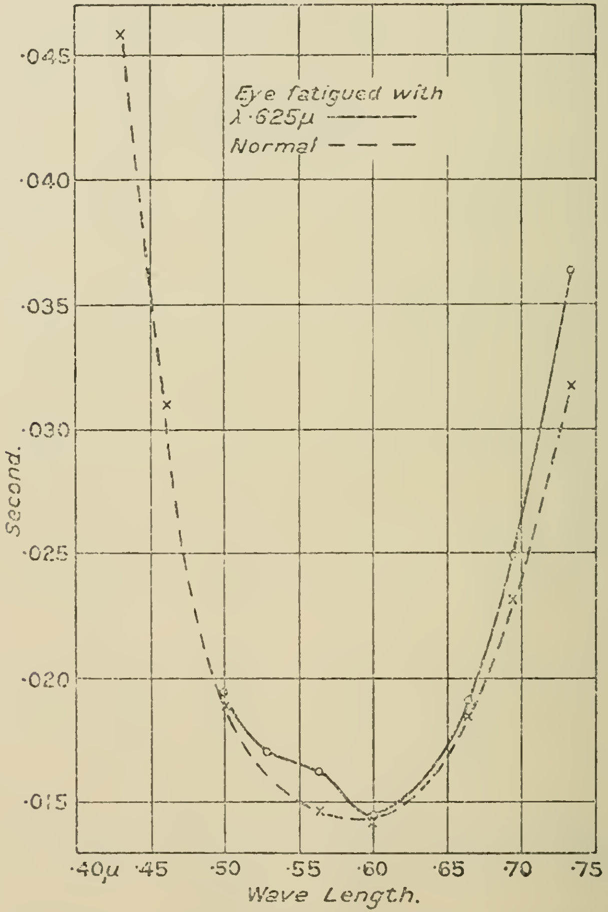


Fig. 7.

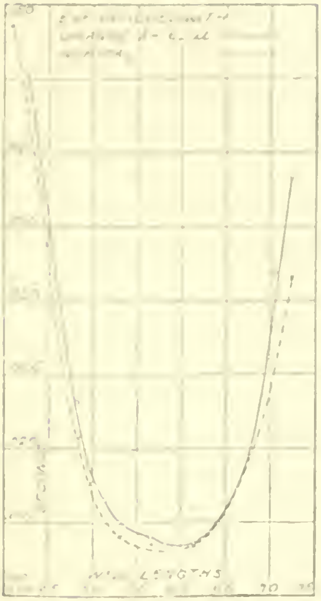
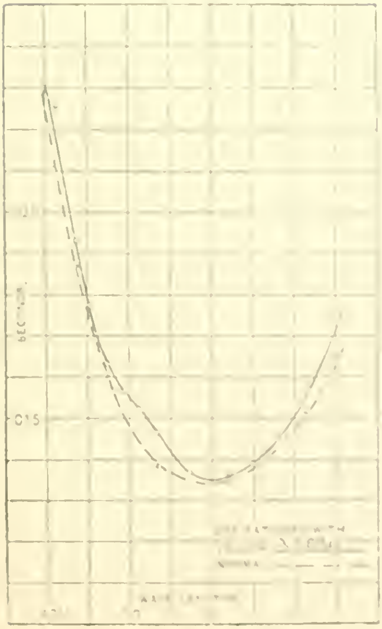
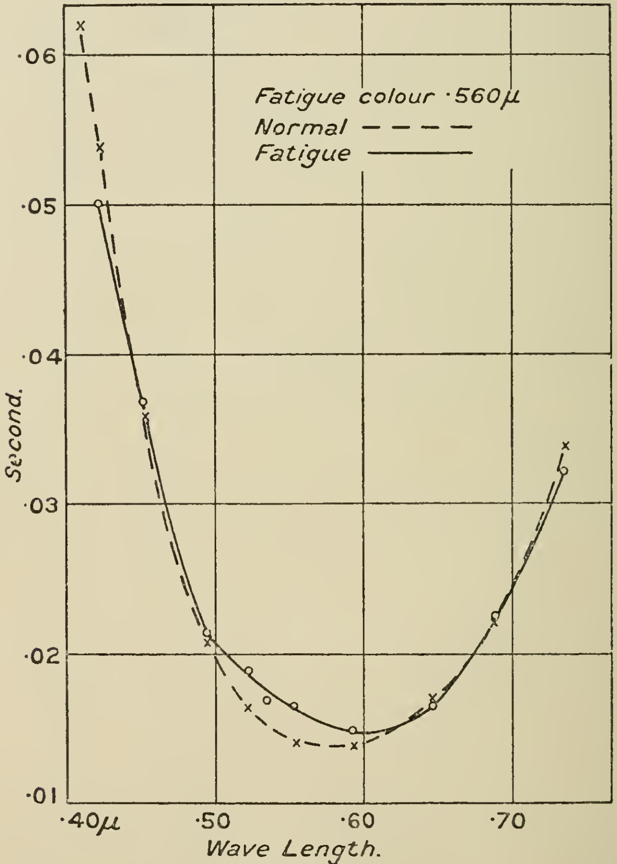


Fig. 8.



The persistency curve obtained when the eye was fatigued with the wave-length λ ·620 μ is here reproduced in fig. 7 from a previous paper to which reference has already been made. This curve is of the double red and green elevation type, similar to the curves of the two figures immediately preceding.

Fig. 9.



Further consideration led to the conclusion that a second transition point ought to exist between curves of the double red and green elevation type and those of the single green elevation type. Since the curve for the wave-length λ ·520 μ, fig. 13, was known from a previous investigation, persistency curves were successively determined with the fatiguing colours λ ·560 μ and λ·540 μ. The data for these are given in Table V. and Table VI., and are plotted in fig. 9 and fig. 10 respectively. Both curves, it will be noticed, are characterized by a single elevation in the green.

Fig. 10.

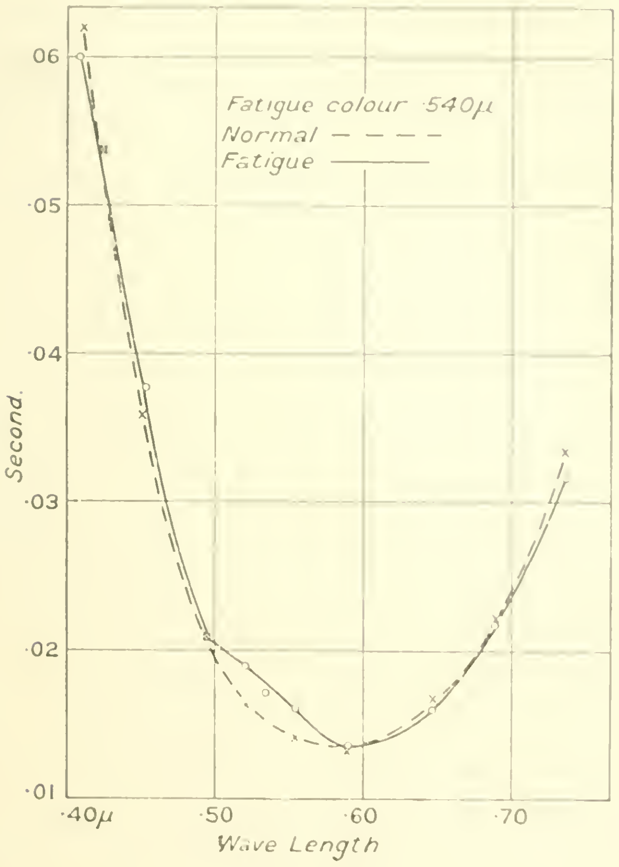


TABLE V.

λ.	Normal Persistence.	Eye fatigued with λ ·560 μ.	λ.	Normal Persistence.	Eye fatigued with λ ·560 μ.
·735 μ	·0337 sec.	·0323 sec.	·522 μ	·0161 sec.	·0189 sec.
·690	·0221	·0224	·495	·0209	·0214
·647	·0167	·0164	·453	·0360	·0380
·593	·0137	·0144	·423	·0538	·0500
·553	·0141	·0164	·410	·0620	
·535	...	·0169	...	...	

TABLE VI.

λ.	Normal Persistence.	Eye fatigued with λ ·540 μ.	λ.	Normal Persistence.	Eye fatigued with λ ·540 μ.
·735 μ	·0337 sec.	·0318 sec.	·522 μ	·0164 sec.	·0190 sec.
·690	·0221	·0218	·495	·0209	·0209
·647	·0167	·0161	·453	·0360	·0378
·593	·0137	·0138	·423	·0538	·0538
·553	·0141	·0161	·410	·0620	·0602
·535	...	·0171	...	...	...

Since the persistency curve for the wave-length λ ·577 μ, fig. 11, had previously been determined to be of the double red and green elevation type, it was evident that the transition point must be near λ ·570 μ. This hue was then used as the

Fig. 11.

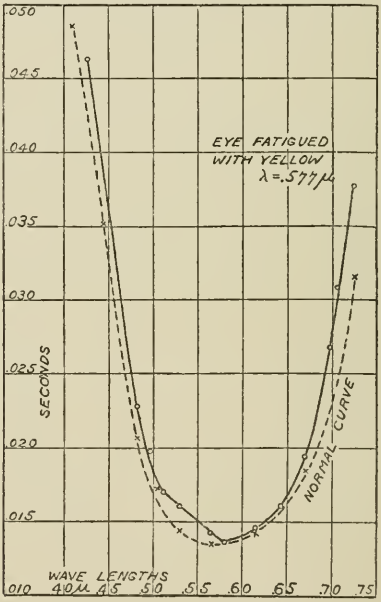


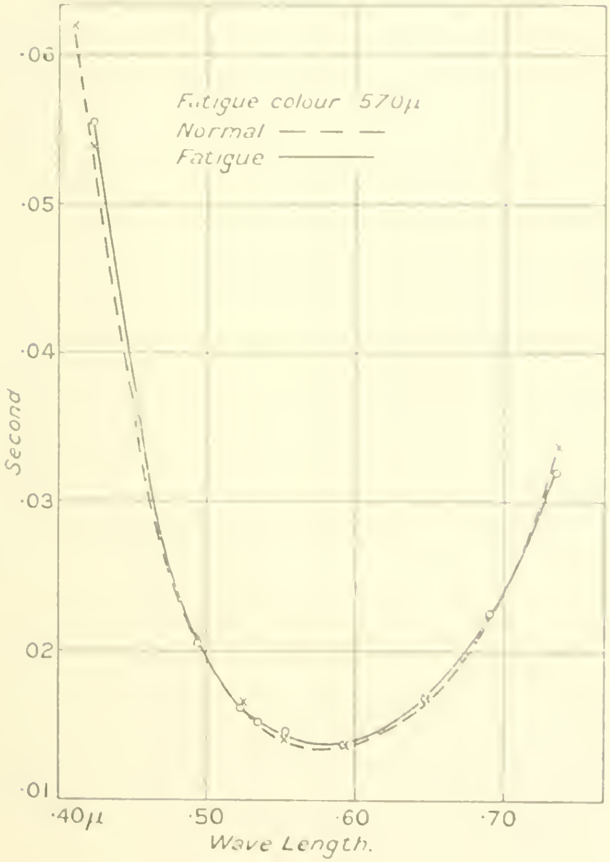
TABLE VII.

λ.	Normal Persistence.	Eye fatigued with λ ·570 μ.	λ.	Normal Persistence.	Eye fatigued with λ ·570 μ.
·735 μ	·0337 sec.	·0320 sec.	·522 μ	·0164 sec.	·0163 sec.
·690	·0221	·0224	·495	·0209	·0205
·647	·0167	·0168	·453	·0360	·0365
·593	·0137	·0137	·423	·0538	·0554
·553	·0141	·0146	·410	·0620	...
·535	...	·0153	...	...	...

fatiguing colour, and the results given in Table VII. obtained from which the curve in fig. 12 is plotted.

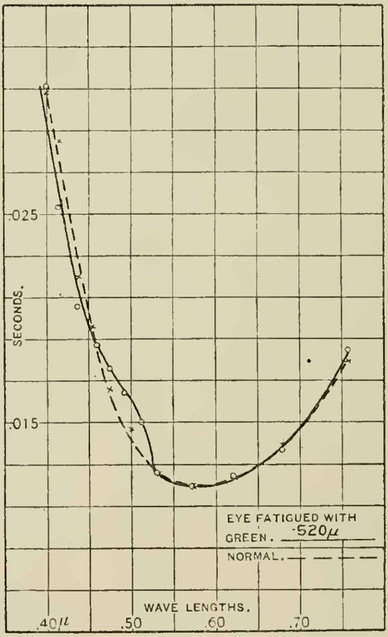
This curve, like that for the first transition point, has no elevations, but coincides at all points with the normal.

Fig. 12



It was now certain that two more transition points existed, one between the single green elevation type of curve, such as that for the wave-length λ ·520 μ, fig. 13, and the double green and violet elevation type, like that for the wave-length λ ·440 μ, fig. 16; and the other marking the transition from this latter type of curve to the single violet elevation type exhibited by that obtained for the wave-length λ ·400 μ, fig. 17, which was known from previous work*.

Fig. 13.



In the process of narrowing down the third transition

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* Note.—The readings obtained when the eye was fatigued with the wave-lengths λ ·440 μ and λ ·400 μ are given in the paper already referred to, viz.: "Effect on Persistence of Vision, etc.," Phys. Rev. vol. xi. By some oversight the corresponding normal persistency readings were omitted from that paper, and they are now given here:—

λ.	Normal Persistence.	λ.	Normal Persistence.	λ.	Normal Persistence.
·758 μ	·0182 sec.	·622 μ	·0113 sec.	·428 μ	·0203 sec.
·715	·0156	·573	·0105	·409	·0249
·680	·0134	·507	·0120	·400	·0277
·647	·0121	·465	·0154	...	...

region, the wave-lengths λ·480 μ and λ·460 μ were successively used as fatiguing colours, for which the results in Table VIII. and Table IX. were obtained.

TABLE VIII.

λ.	Normal Persistence.	Eye fatigued with λ·480 μ.	λ.	Normal Persistence.	Eye fatigued with λ·480 μ.
735 μ	·0230 sec.	·0234 sec.	·522 μ		·0150 sec.
690	·0171	...	490	·0171 sec.	·0168
647	·0147	·0147	453	·0246	·0244
593	·0150	·0133	423	·0312	·0309
553		·0134	410	·0368	·0351
·535	·0138	·0141	400	·0452	·0425

TABLE IX.

λ.	Normal Persistence.	Eye fatigued with λ·460 μ.	λ.	Normal Persistence.	Eye fatigued with λ·460 μ.
735 μ	·0230 sec.		490 μ	·0171 sec.	·0176 sec.
690	·0171	...	453	·0246	·0249
647	·0147	...	423	·0312	·0311
593	·0150	·0124 sec.	417	...	·0341
553		·0132	410	·0368	·0378
535	·0138	·0137	405	...	·0418
522	...	·0150	400	·0452	·0426

These curves are exhibited in fig. 14 and fig. 15 respectively. They show no elevations at all, but are coincident with the normal curves. The conclusion appears to be that this transition region is broader than those previously described, probably because the dispersion of the blue in the prismatic spectrum is greater than that of the red. The wave-lengths λ·480 μ and λ·460 μ may be regarded, therefore, as marking the edges of the transition band, the centre being the wave-length λ·470 μ. For this colour no persistency curve was considered necessary. The curve with the wave-length λ·480 μ, fig. 14, appears to retain a slight vestige of the green elevation which I have indicated by altering the curve at "[illegible]."

The fourth and last transition point obviously must lie between the wave-lengths λ·440 μ and λ·400 μ, since the curve for the former, fig. 16, has two elevations in the green and the violet regions, and that for the latter, fig. 17, only one in the violet. The colour λ·420 μ was selected for the first trial. This proved to be the desired point, and no other

Fig. 14.

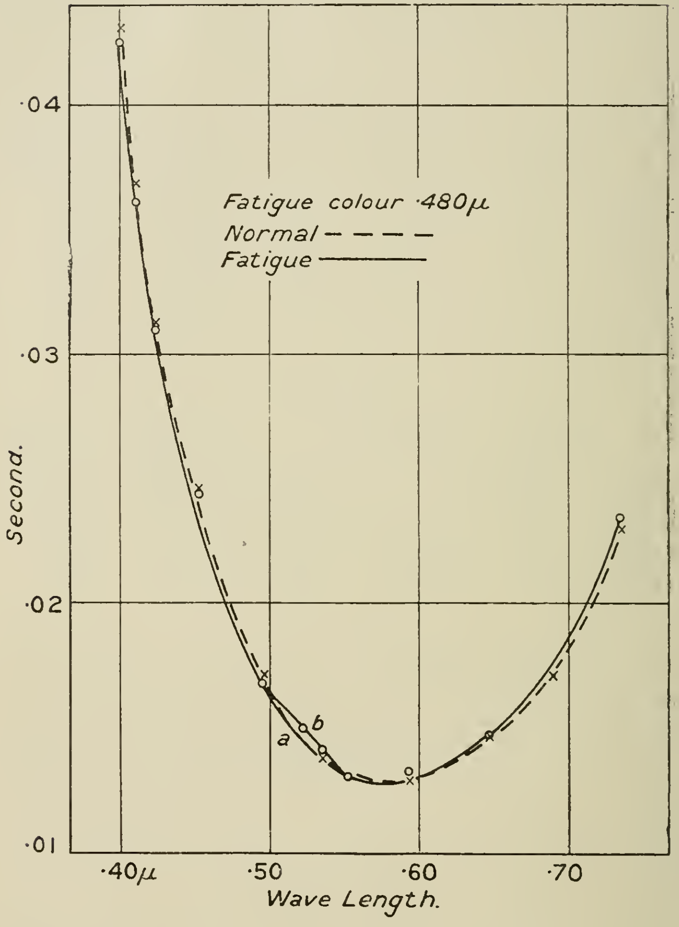
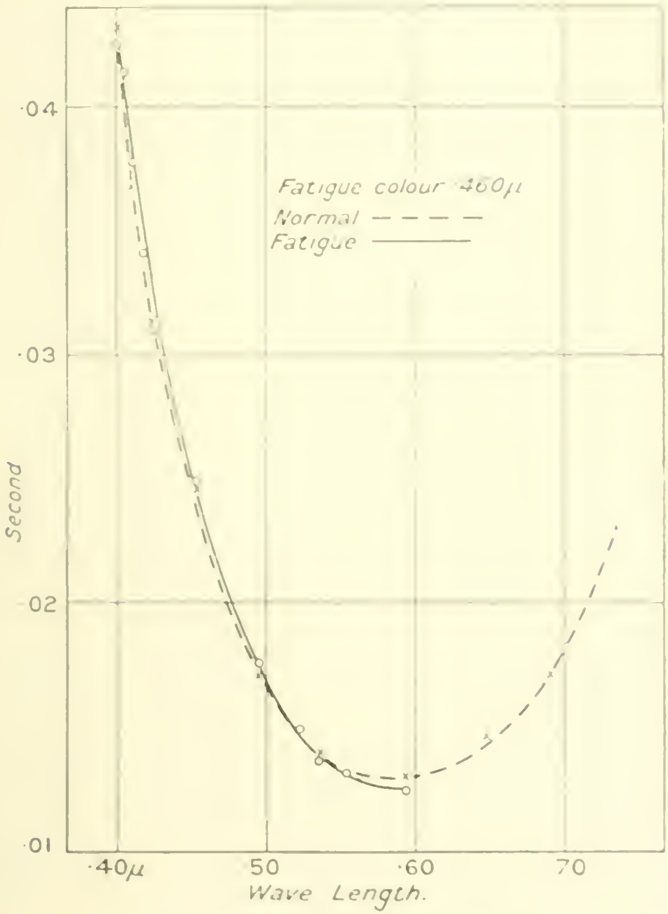


TABLE X.

λ.	Normal Persistence.	Eye fatigued with λ ·420 μ.	λ.	Normal Persistence.	Eye fatigued with λ ·420 μ.
·705 μ	·0262 sec.	·0262 sec.	·465 μ	·0275 sec.	...
·665	·0169	·0175	·448	·0336	·0339 sec.
·626	·0144	...	·430	·0392	·0385
·577	·0143	·0145	·424	...	·0415
·540	·0156	·0153	·417	·0450	·0446
·512	·0183	·0179	·410	...	·0487
·488	·0219	·0215	·405	·0530	·0556

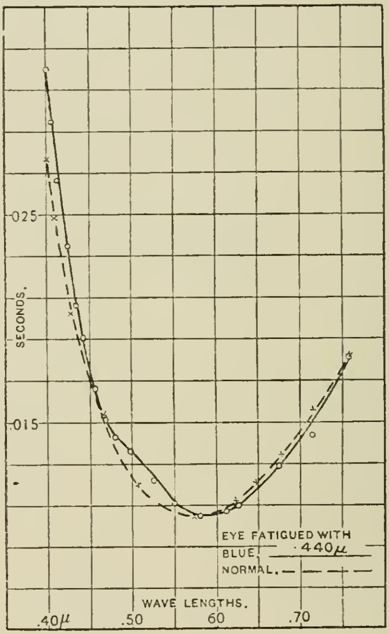
colours on either side were tried. The readings are shewn in Table X. and plotted in fig. 18. This curve is without any indication of elevations, and coincides throughout its course with the normal.

Fig. 18.



In order to exhibit the seventeen curves described in the preceding pages comprehensively in a simple figure (fig. 19), they have all been replotted so as to make the normal curve a straight line by reducing its scale in all parts to the arbitrary value of 100, and the values of the abnormal curves in the same ratio. Slight departures of the abnormal from the normal curves have been ignored, long experience having shown that they are without significance, and to be attributed rather to the inevitable errors of observation.

Fig. 16.

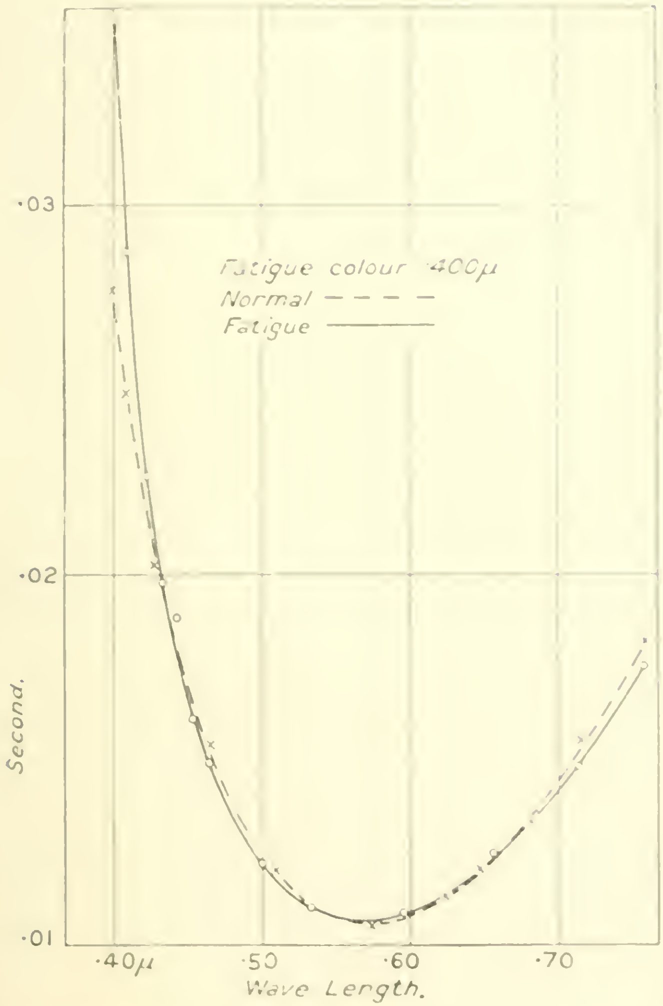


The elevations of the curves, both single and double, can be readily recognized and compared, and their limiting wave-lengths noted. As they are arranged in ascending order of wave-lengths, with the shortest, violet, at the bottom, the curves for the four transition points fall into their proper places, and show their relation to the curves of the other types. Each band of colour used for fatiguing the eye is indicated by a short vertical line just above the normal curve.

Finally, the seventeen curves have been consolidated into a single composite curve by taking the mean values for all the elevations of all the curves. These values are shown in

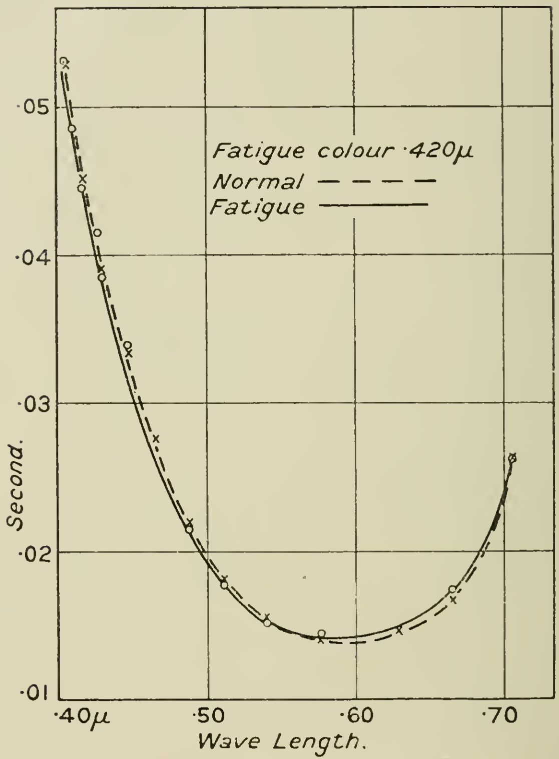
Table XI., and are plotted on an enlarged scale in fig. 20. The four transition points are indicated by short vertical

Fig. 17.



lines as before, and are arranged in pairs quite symmetrically situated in relation to the two minima of the curve.

Fig. 18.



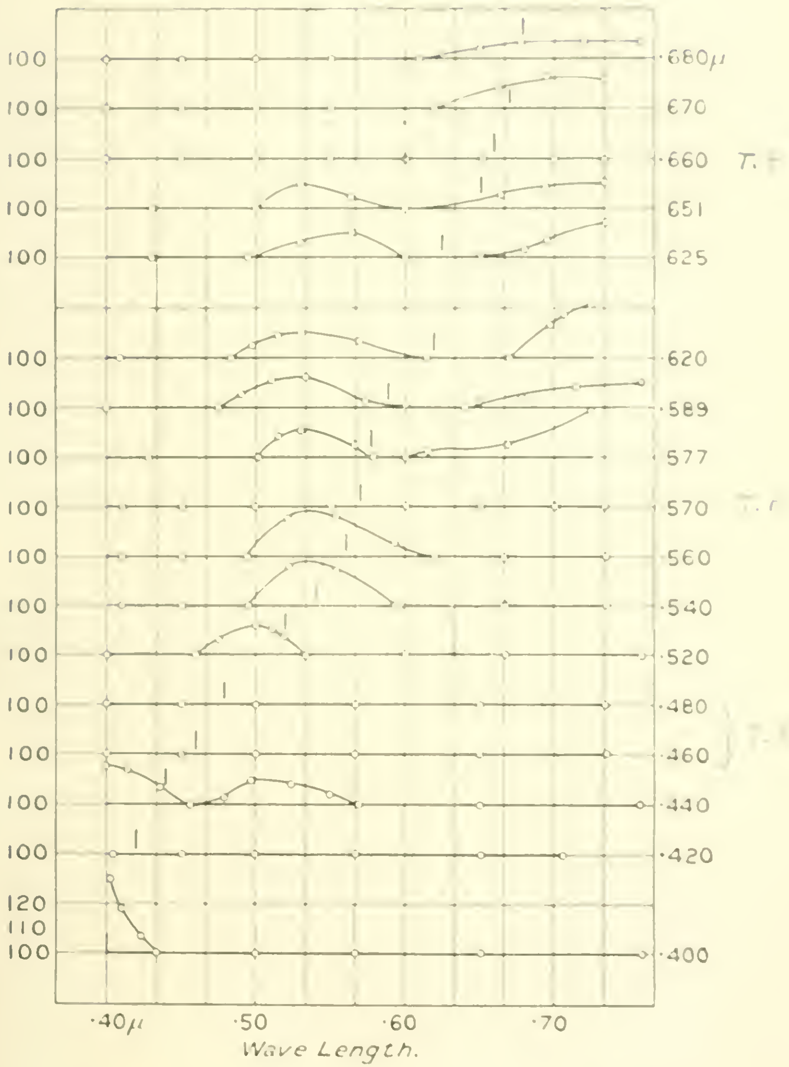
The three elevations of this curve are strongly indicative of a trichromatic basis for the perception of colour.

TABLE XI.

λ.	Mean Ratio.	λ.	Mean Ratio.	λ.	Mean Ratio.	λ.	Mean Ratio.
·400 μ	122	·480 μ	104·7	·566 μ	105	·663 μ	106
·415	114	·490	106	·600	100·7	·677	108
·423	110	·500	107·5	·620	100·7	·695	110
·433	107	·515	109·5	·630	101·7	·715	111
·455	100	·523	112	·640	102·5	·733	112
·470	102·7	·550	109	·650	104	·758	110

The general results in this paper may be represented diagrammatically as in fig. 21. In this diagram the indicated wave-lengths mark the transition points and divide the spectrum into five parts. It is evident that the fundamental

Fig. 19.



red sensation corresponds to some hue between the beginning of the red and the point of transition at λ ·660 μ. Similarly, the fundamental green sensation is excited by some portion of the spectrum lying between the second and third transition points at the wave-lengths λ·570 μ and λ·470 μ. Finally, the third fundamental sensation, which must be violet and not blue as many colour-theorists allege, lies between the fourth point of transition at λ·420 μ and the end of the violet. It is to be regretted that this method of investigation does not yet enable us to discover the exact fundamental hues. It is possible that the method of fatiguing the eye with carefully selected pairs of colours at one time, such as I have used in another investigation*, or even with three colours simultaneously, will bring the desired precision. Undoubtedly such investigations will elicit much new information on the complex and apparently inexhaustible phenomena of colour-vision.

Fig. 20.

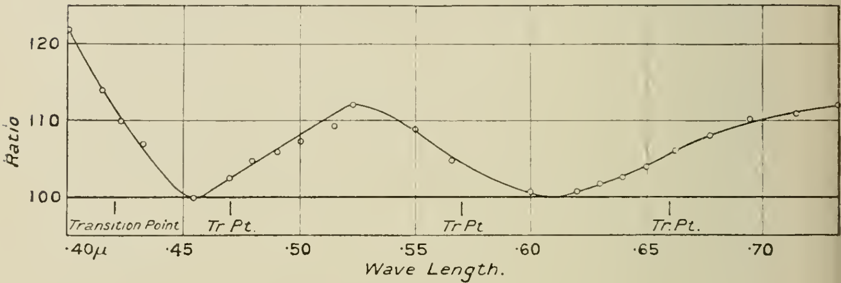
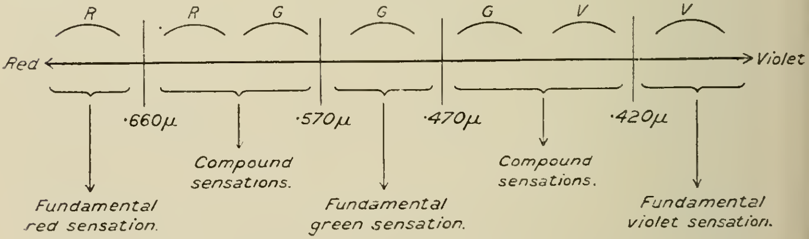


Fig. 21.


R
R
G
G
G
V
V
Red
Violet
·660μ
·570μ
·470μ
·420μ
Compound sensations.
Compound sensations.
Fundamental red sensation.
Fundamental green sensation.
Fundamental violet sensation.

One of the most persistent problems in colour-vision is the proper disposition of yellow. In purity of appearance it seems to have quite as much claim as red and green to be regarded as primary in its nature. Indeed, the psychologists quite universally recognize fully the primary quality of the sensation of yellow. But the five persistency curves obtained between the wave-lengths λ·660 μ and λ·570 μ are identical in their nature, and therefore in the conclusions to be drawn from them. This region includes orange as well as yellow. No one doubts that orange is a compound sensation; and since, according to the curves, the purest yellow has precisely the same effect on the eye, it must likewise be a compound sensation. The same reasoning applies to blue, which also must be compound in its nature.

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* "Some Phenomena of the Persistence of Vision," Phys. Rev. vol. xxviii. (1909).

The existence of three sharply-defined regions of the spectrum exhibiting curves of the single elevation type, corresponding to red, green, and violet, proves conclusively the existence in the eye of three primary sensations corresponding to these colours. The concurrent evidence that yellow and blue are compound sensations completes the proof.

The evidence presented in this paper for the existence of but three fundamental colour-sensations is entirely the result of experiments made upon the normal retina. This may be supplemented and greatly strengthened by comparison with persistency curves obtained by persons who are colour-blind. In a former investigation * I studied by this method twenty-seven cases of abnormal colour-vision; and in fig. 22, from that paper, there are shown six out of the seven representative classes into which cases of colour-blindness naturally fall. The persistency curves are drawn after the manner of those in fig. 19: the straight horizontal line at O is my own normal curve, and the other compared with it is that obtained by the colour-blind person. These curves were determined when the eyes were not fatigued, but were rested in ordinary daylight.

In fig. 22 Class I. is a curve with one elevation in the red, indicating red-blindness; Class II. shows one elevation in the green, the characteristic of green-blindness; Class III. shows two elevations, one in the red and the other in the green, indicating a type of blindness involving those two colours; Class IV. is a modification of the same type as Class III.; Class V. has two elevations, one in the red and the other in the violet, another type of colour-blindness involving two colours; Class VI. has two elevations, one in the green and the other in the violet, still another type, being the third possible variety of colour-blindness involving two colours; Class VII. is that of a totally colour-blind person, and shows the elevation of the whole curve. These persistency curves for eyes that are naturally colour-blind show exactly the same elevations that are obtained for the normal eye when fatigued

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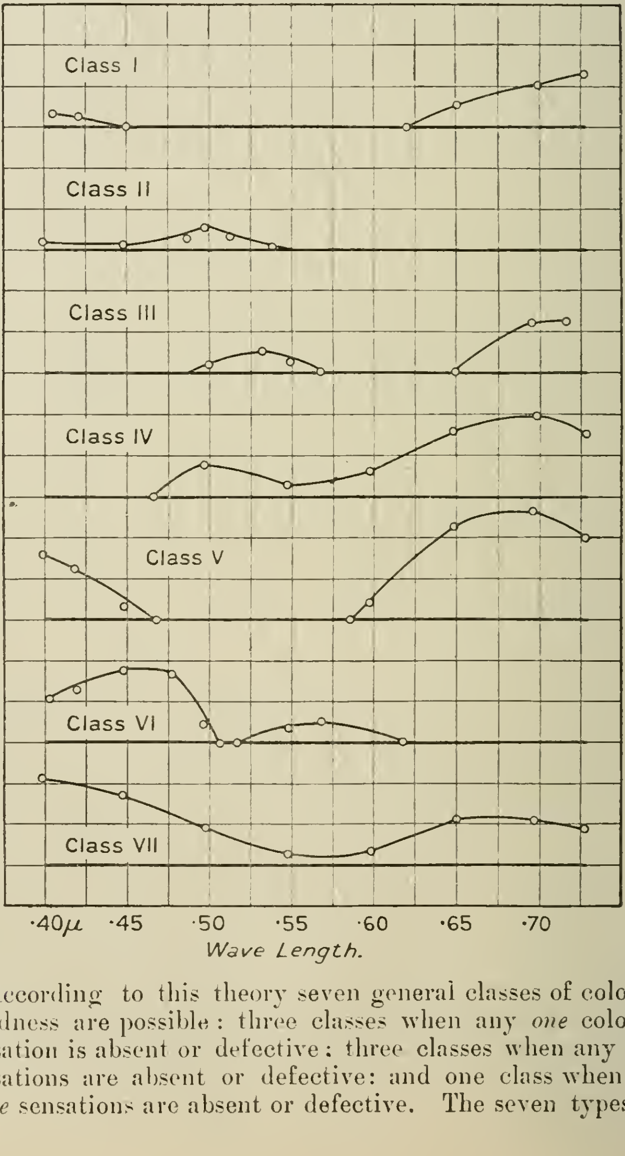
* "Persistence of Vision in Colour-blind Subjects," Phys. Rev. vol. xv. (1902).

by various spectral colours. These curves for colour-blindness, therefore, constitute strong additional evidence for the existence of three primary colour-sensations—red, green, and violet.

Fig. 22.



According to this theory seven general classes of colour-blindness are possible: three classes when any *one* colour-sensation is absent or defective: three classes when any *two* sensations are absent or defective: and one class when *all three* sensations are absent or defective. The seven types of curves in fig. 22 show all these classes excepting only that for violet colour-blindness, for which type I have not yet found a subject.

For the purpose of comparison, I have brought together the exact lines of the primary colours according to several investigators whose experiments were conducted on the basis of the trichromatic theory. With these are included the colours selected by Hering for his theory of colour-vision, and those determined for the same theory by the accurate experiments of Baird *.

	Red.	*Green.*	*Blue.*
Helmholtz	[illegible] red [illegible] of spectrum	[illegible] μ to ·5[illegible] μ	(Ultramarine-blue)
König	Purple-red, just outside spectrum	·505 μ	·470 μ
Exner	Red complementary to ·494 μ (About ·66 μ)	·508 μ	·475 μ
Abney	Between end of spectrum and ·66 μ.	·570 μ to ·470 μ	Varies between ·420 μ and end.

	Red.	*Green.*	*Yellow.*	*Blue.*
Hering	Purple-red (compound).	·495 μ	·574 μ	·471 μ
Baird	Purple-red (compound)	·500 μ	·570 μ	·460 μ

There is no conflict necessarily arising between my own fundamental lines for red and green and those of Helmholtz, Konig, and Exner; there is divergence in the case of violet. But if it is at all justifiable for Helmholtz and the others to differ in their green lines by nearly ·06 μ, no exception need be taken to my violet determination because it differs from the others by an equal amount.

In endeavouring to connect the transition points with other colour-phenomena, I have found specially suggestive the colour-sensation curves obtained by Abney and Watson, fig. 23, and by Konig and Dieterici, fig. 24. On each of these figures I have indicated the transition points by short vertical lines with wave-lengths attached.

In the curves of Abney and Watson the transition points λ·660 μ and λ·470 μ are practically at the ends of the sensation curve for green; and the remaining transition points at λ·420 μ and λ·570 μ are near the ends of the sensation curve for blue. While the green and red sensation curves extend to the wave-length λ·43 μ, yet their influence compared with blue seems quite negligible on the more refrangible side of λ·470 μ. The transition point at λ·570 μ is also very close to the intersection of the green and red sensation curves. The transition point at λ·420 μ is shown by the curves to be practically outside the influence of the red and green sensations, and hence may be regarded as a region of a single

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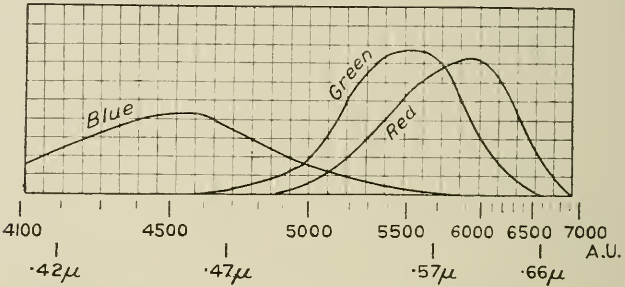
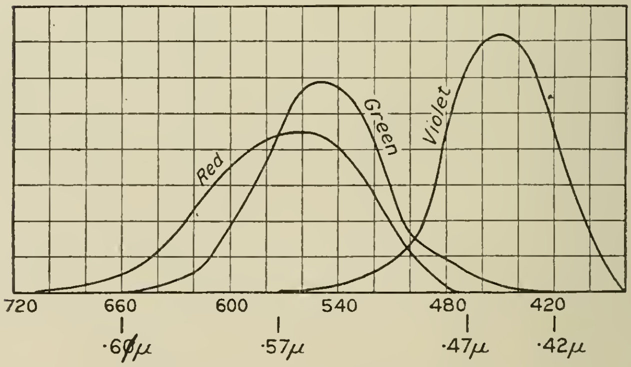
* J. W. Baird, "The Colour Sensitivity of the Peripheral Retina," Carnegie Institution, 1905.

Fig. 23.



Normal Sensation Curves. (Abney and Watson.)
(From Parsons's 'Colour Vision,' p. 244.)

Fig. 24.



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Sensation Curves. (König and Dieterici.)
(From Parsons's 'Colour Vision,' p. 222.)

pure-colour sensation. Similarly, the spectral region from the transition point λ·660 μ to the end of the spectrum is pure red free from the influence of the other two sensations.

The sensation curves of König and Dieterici, fig. 24, show some differences. The ends of the green sensation curve are the transition points λ·660 μ and λ·420 μ, while the transition point λ·470 μ is still the more refrangible end of the sensation curve for red. The transition point λ·570 μ

tion
marks one end of the sensitive curve for violet. It will be noticed that the regions between the transition points λ ·660 μ and λ ·420 μ and the respective ends of the spectrum are, as before, characterized by purity and simplicity of colour-sensation. The transition point at λ ·570 μ is again at the intersection of the red and green sensation curves, that is, where the two sensations balance the influence of each other, without sufficient of the third sensation to make itself perceptible. In both figures one can see reasons why the regions between λ ·420 μ and λ ·470 μ, and between λ ·570 μ and λ ·660 μ, should be characterized by compound sensations. But it is difficult to understand why the exceedingly complex region between λ ·470 μ and λ ·570 μ should exhibit, as it does, persistency curves with only one elevation in the green.

The occurrence of the four transition points at the boundaries of the sensation curves cannot be in any sense accidental, and is certainly not intentional, since the transition points were discovered long before any examination of the sensation curves was made in this connexion.

The cumulative effect of all the experimental evidence presented in this paper seems to warrant most strongly the conclusions already expressed, that there are but three colour sensations, which correspond to red, green, and violet, and that these sensations are primarily excited by hues which lie between the limits set by the four transition points.

Persistence of Vision and the Primary Color Sensations

By

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Persistence of Vision and the Primary Color Sensations

Frank Allen, Ph.D., F.R.S.C.

WITH the exception of astronomy perhaps no branch of science extends so far back in history as the study of color vision. The reason for this is obvious. Color in nature is displayed on so magnificent a scale that minds at all observant could not fail to be impressed. The records of Babylon and of Egypt do not give much information of a scientific nature, due perhaps to their custom of jealously confining such knowledge to the guilds of priests. But the Greek philosophers, from Pythagoras onward, with their marvelous aptitude for speculative inquiry, manifested the most extraordinary ingenuity in devising explanations regarding the origin of color and the nature of its perception. Pythagoras entertained a corpuscular theory of light. Empedocles and Plato imagined vision to be a species of the sensation of touch excited by invisible feelers having their origin in the eye; Epicurus believed that we see by the intervention of light as we feel an object by means of a stick; Aristotle urged that color is due to the mixture of darkness and white light; or, in modern terms, that the mixture of something with nothing in varying proportions gives an infinite variety of something else. This hypothesis of Aristotle was enthusiastically adopted by the German poet Goethe and advocated by him with an accompaniment of highly vituperative abuse directed against the illustrious Newton and his theory of colors

Despite manifold attempts to explore the fascinating field of color, the subject lay wrapped in mystery until Newton with his prism dispersed white light into its color components, and enunciated the simple but sufficient principle that "to the same degree of refrangibility ever belongs the same color, and to the same color ever belongs the same degree of refrangibility." The uniform failure of all attempts to explain colors before Newton's success lay in the universal assumption that white light was a pure entity in itself. Once the fact was recognized that white light is a mixture of colors, progress became rapid and certain.

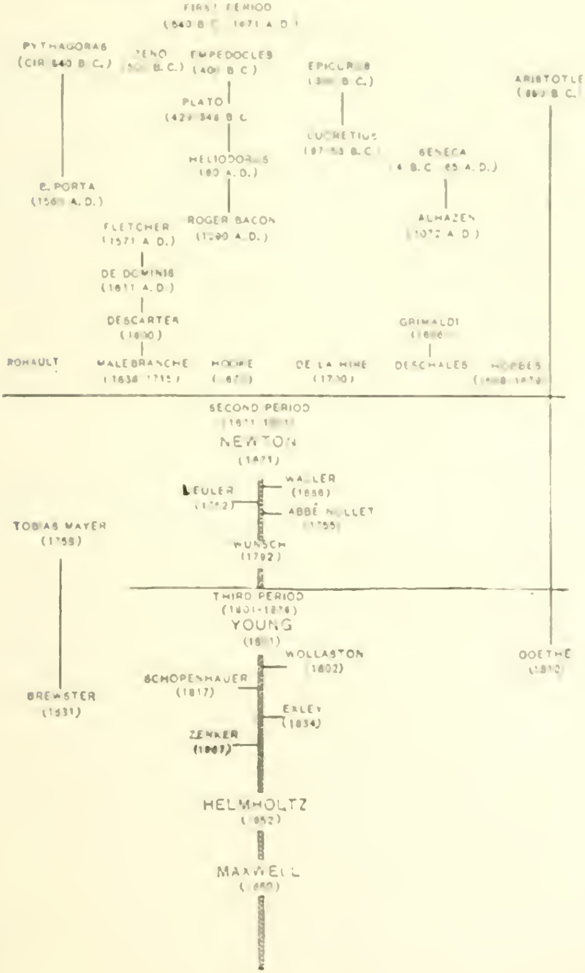
We do not need to discuss here the history of Newton's corpuscular theory of light and its triumphant rival, the undulatory theory of Huygens. But it will not be out of harmony with the title of this paper to note a peculiar use which was made of the persistence of vision. One objection urged against the idea that light consisted of streams of swiftly moving corpuscles was that myriads of collisions would occur especially when two streams of light crossed each other's path. But one ingenious writer pointed out that if each "lucid point" on the sun emitted only one hundred and fifty corpuscles per second, they would still give a continuous impression of light, owing to the persistence of vision in the retina, and at the same time the particles of light would be over one thousand miles apart. Surely by this happy supposition the chances of collision were reduced sufficiently to satisfy the most exacting criticism.

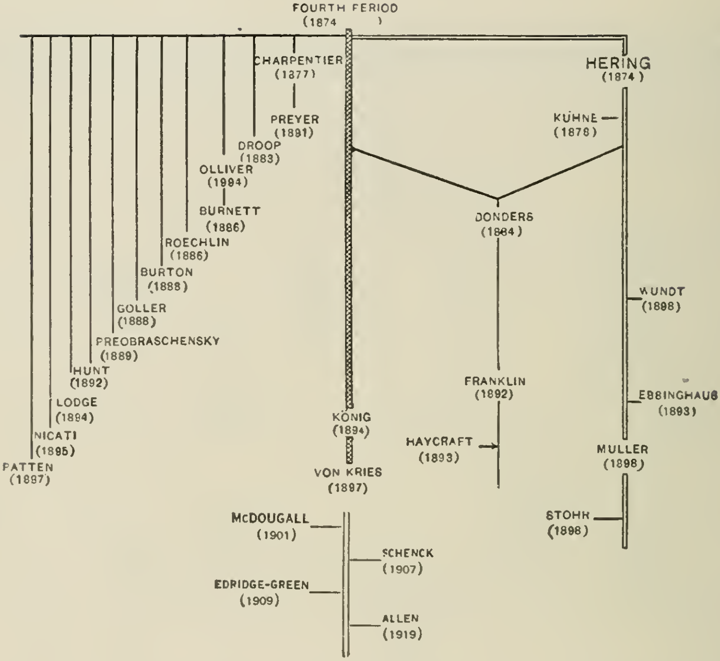
It is doubtful if any subject in science has been the cause of so many speculations and theories. Nor are the controversies by any means settled today. Scarcely a year passes without a new theory of color vision being advanced by some ambitious scientist whether he be a physicist, psychologist or physiologist. In many cases the paper announcing the birth of the new theory constitutes also its obituary notice. The sciences of physics and chemistry, of physiology and psychology, have been diligently searched for principles, one seemingly more inapplicable than another in order to account for the transformation of the energy of the ethereal waves into the diversified hues of color.

To the general problem of vision was added the interesting and important fact that it was necessary to assume only a limited number of color sensations to provide for the perception of an unlimited number of hues and tints of color. It is largely conflicting views as to the number and nature

TABLE I

HYPOTHESES OF COLOR VISION





of these primary color processes that cause the battlefield of color vision to be so littered with the remains of the dialectically slain.

That this is no mere figure of speech may be seen from the preceding genealogical tree of color vision which I published in the *Physical Review*. This also has the advantage of exhibiting the main line of development from Newton, and the subsidiary line due to Hering together with the positions of theories of secondary importance. Some guiding principle such as this diagram affords will enable the reader of the voluminous literature of color vision to trace his steps without confusion.

The main controversy today is between the theory of Hering and that of Young modified by Maxwell, Helmholtz and others. As is well known the latter and far older theory, adopted generally by physicists, provides for three color sensations, red, green, and either blue or violet; while the theory of Hering adopted largely by psychologists provides three antagonistic pairs of color sensations, red-green, yellow-blue, and white-black. To admit blackness to the rank of sensations seems to the physicist an impossibility in view of the fact that darkness is the absence of light energy. Still so long as crucial experiments to determine the number of primary sensations are lacking no end to the controversy is apparent. I am convinced however that the experiments on the persistence of vision which I have conducted for some years speak on this point with the utmost decision.

As the different colors of the spectrum are designated in this paper by their wave-lengths, it will be useful to remember that the limiting wave-lengths according to Listing are:

Table of Colors and Wave-lengths

.723μ to .647μ—Red
.647μ to .585μ—Orange
.585μ to .575μ—Yellow
.575μ to .492μ—Green
.492μ to .455μ—Blue
.455μ to .424μ—Indigo
.424μ to .397μ—Violet

The apparatus used in all my researches in color vision was arranged according to the diagram in Fig. 1. Light

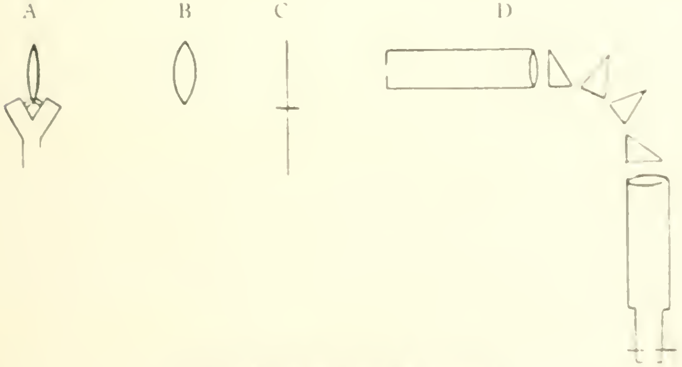


Figure 1. Ensemble of Apparatus.
A, flame; *B*, lens; *C*, disc and *D*, spectrometer.

from an acetylene flame passed through a disk with two opposite open sectors of ninety degrees each, whose speed of rotation was recorded electrically upon a chronograph reading to the ten-thousandth part of a second. The flickering light entered a spectrometer and was viewed as a spectrum in an eyepiece with adjustable shutters which enabled all the spectrum to be cut off except a narrow vertical band of the desired wave-length. In making measurements the speed of the disk was regulated so that the flickering of the light in the eyepiece became just imperceptible and was then recorded. One quarter of the time for one complete rotation of the disk is therefore the measure of the persistence of the vision, or the duration of the undiminished intensity of light upon the retina. By many writers this is called the critical frequency of flicker.

When it became necessary to fatigue the eye by exposing it to some bright spectral color of known wave-length, a second spectrometer was used with an arc light as the source of color. An eyepiece with adjustable shutters isolated a suitable band of the spectrum which was used to fatigue the eye with which observations of the persistence of vision were made. An interval of three minutes was allowed for the fatiguing process before each measurement of the persistence of vision was taken upon the colors in the first spectrometer. In this way a persistency curve for the whole spectrum was obtained which can be compared with a normal curve previously determined when the eye was adapted for diffused daylight.

The first question that arises is: Are we justified in assuming the retina to be normal when in diffused daylight? It was formerly thought that the normal retina was obtained only after resting it in complete darkness. Experiments made under various conditions of adaptation have altogether changed this idea.

The writer has made a series of persistency curves by resting the eye, (a) in a dimly lightly "dark-room;" (b)

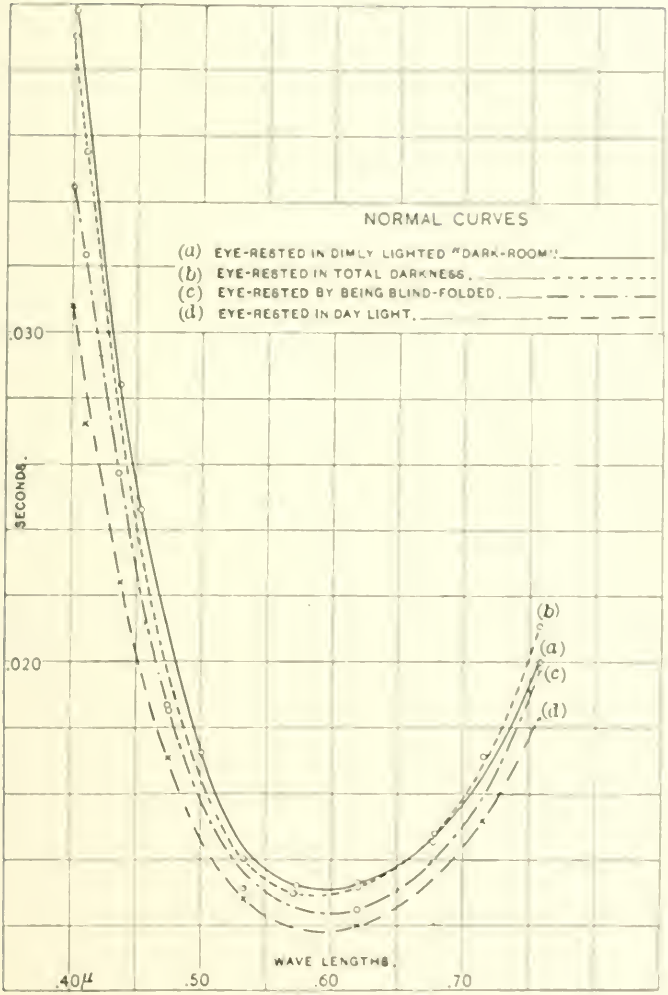


Figure 2. Persistency Curves through Resting the Eye.

in total darkness; (c) by being blindfolded; (d) in diffused daylight. These curves are shown in Fig. 2. In the first three cases the values of the duration of color impressions are greater than for daylight adaptation, the greatest difference being obtained when the eye was rested in partial darkness. This is probably due to the fatiguing of the retina by the effort to distinguish dimly illuminated objects. If we compare this figure with those obtained later when the eye was fatigued with different colors it will be noticed that the abnormal curves are always elevated above the normal. Whether, then, the retina is under the influence of direct rays of light or of darkness it is in an abnormal condition.

By comparing the amount of elevation of the three curves in this figure it is found that the values of the persistency increase from three per cent in the orange to twelve per cent in the extreme red and to thirty per cent in the extreme violet. Therefore the change in the sensitiveness for light which is produced in a retina placed in the dark is not equal for rays of different refrangibility.

The adaptation of the retina in the darkness is not sudden but progressive. Some experiments were made to determine this. The time of the persistence of vision for the normal retina was measured for the four colors .650μ, .567μ, .505μ, and .463μ. Then the eye was blindfolded for intervals of one, three, five, ten and fifteen minutes, and corresponding persistency measurements were made after each. A series of curves of the "saturation" type was obtained which are shown in Fig. 3. As far as the persistence of vision is concerned the saturation point is reached in five minutes. The delicacy of this system of measuring is well shown in the curve for the wave length 0.567μ where the whole curve is confined within the limits of one one-thousandth of a second.

A series of nine persistency curves was made for spectra of varying degrees of luminosity or brightness. These are shown in Fig. 4, the curve for the brightest spectrum being the lowest. These curves are all of the same type, but it

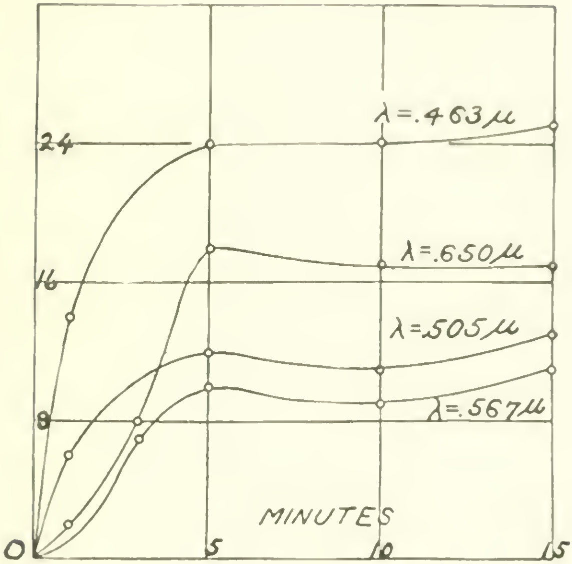


Figure 3. A Series of Curves of the "Saturation" Type.

will be noticed that the lowest point shifts gradually but slightly towards the violet as the spectrum gets less intense. As the lowest point of the curve corresponds to the brightest part of the spectrum, we have here an illustration of the Purkinje effect, viz: that the brightest point of the spectrum is not fixed but varies in position with the brightness, changing from yellow to the green as the spectrum becomes lowered in intensity.

There is a law discovered independently by two scientists, Ferry and Porter, which connects the time of persistence of vision with the luminosity of the light,

$$T = \frac{1}{k \log L}$$

where T is the time, L, the luminosity and k, a constant.

By applying this law to the persistency curves in Fig. 4, we can get a corresponding set of luminosity curves for the same series of spectra we have just been considering. These are shown in Fig. 5. The order of curves is now reversed and the luminosity curve for the brightest spectrum is now the highest, and that for the dimmest spectrum the lowest. It will be noticed how remarkable is the magnitude of the lowering in brightness at the middle of the spectrum compared with the two ends. It would also seem likely that before the spectrum entirely disappears the luminosity curve would become a straight horizontal line.

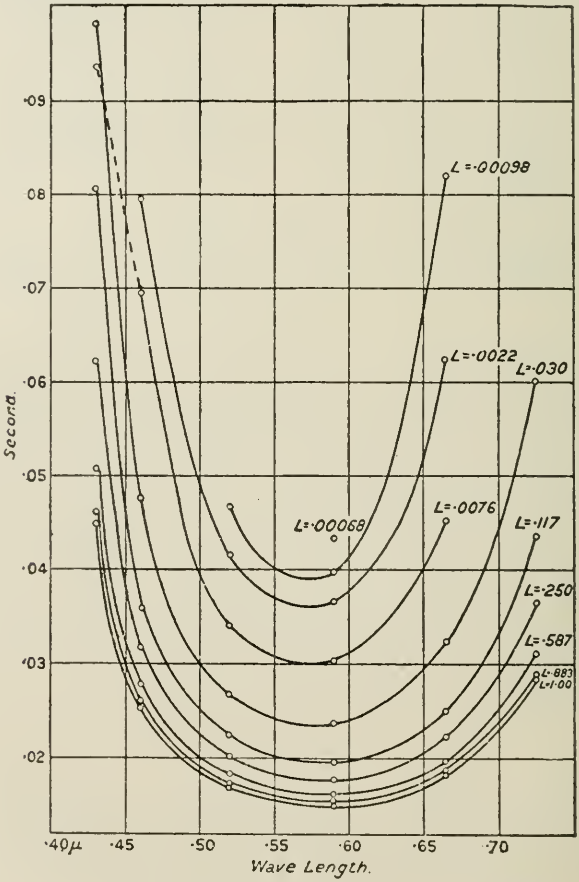


Figure 4. Persistency Curves for Spectra of Varying Degrees of Luminosity.

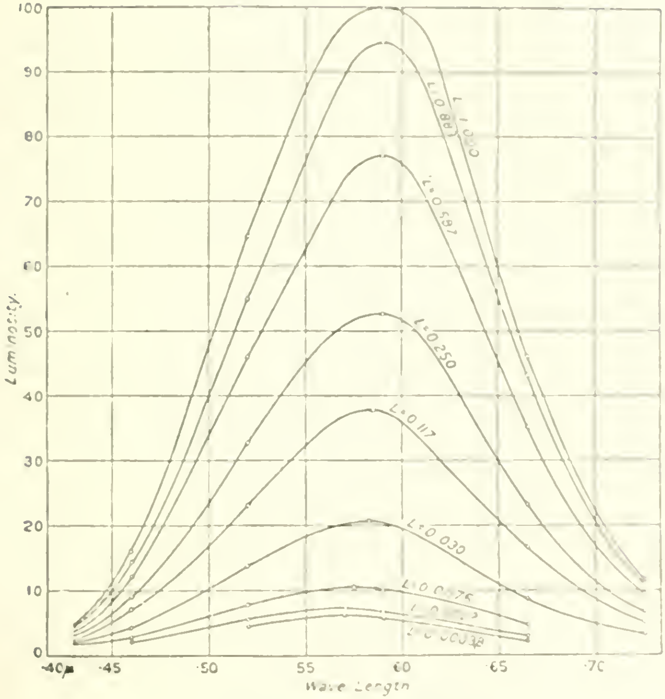


Figure 5. Luminosity Curves.

If, now, for any one wave-length we take the reciprocals of the corresponding values of the persistence of vision for each of the nine curves in Fig. 4. they will, when plotted, give a series of curves as shown in Fig. 6. These curves conform to the equation

$$\frac{1}{T} = k' \log I.$$

Each of these curves consists of two straight lines of different slope, the change in direction occurring very abruptly. The slope of the lower parts of the curves varies in an extraordinary manner, that for the wave-length 0.430μ being quite horizontal.

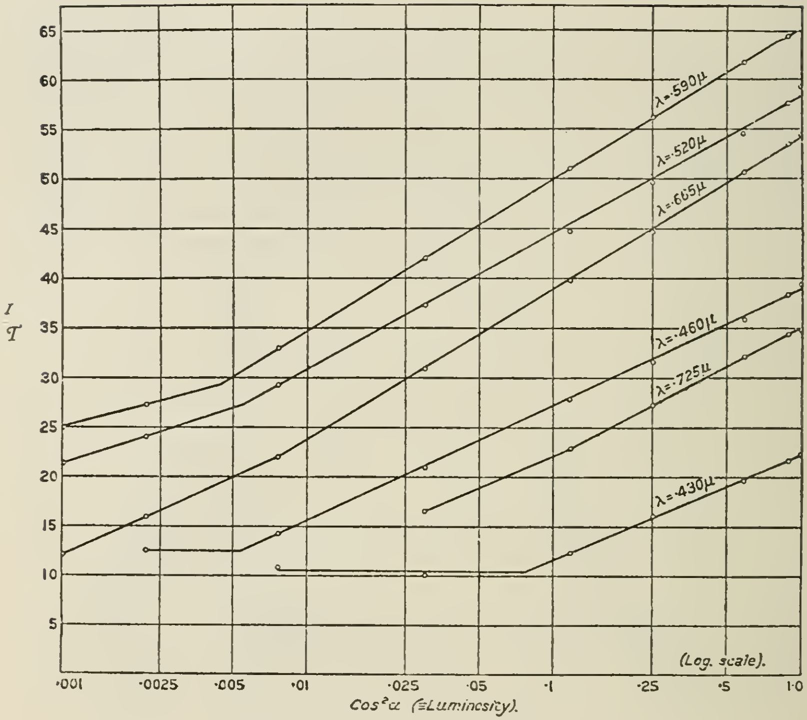


Figure 6. The Relationship between the Reciprocal of the Persistence of Vision Values and the Luminosity.

The explanation of this curious phenomenon is afforded by the duplicity theory of Von Kries, according to which the retinal cones are the parts that function in the perception of very bright light and colors, while the rods perform similar functions for dim light. The upper part of each curve therefore is for cone vision and the lower is for rod vision. The change in direction of the curve shows that the change from one type of vision to the other takes place very abruptly. From the fact that the lower part of the curve for the wave-length 0.430μ is horizontal it would appear that below a certain intensity a change in luminosity does not affect the persistence of vision to any extent.

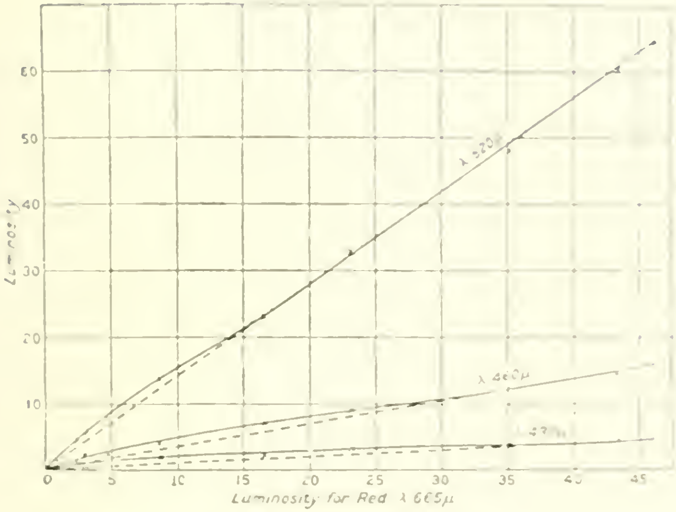


Figure 7. The Purkinje Phenomenon.

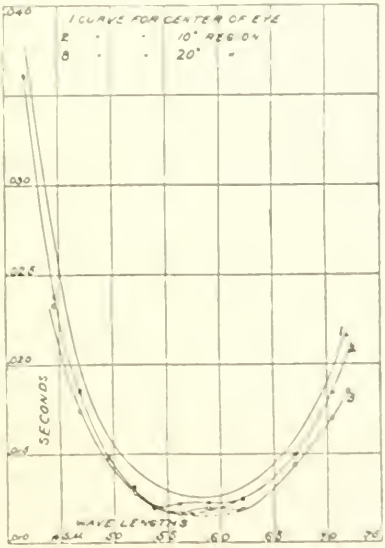


Figure 8. Curve for the Peripheral and Central Persistence of Vision.

The Purkinje phenomenon can also be shown in a very effective manner by the curves in Fig. 7. These are obtained by plotting the values of the luminosity of red of wave-length .665$_\mu$ on the horizontal scale as the standard of reference, and the corresponding luminosities of the colors .520$_\mu$, .460$_\mu$, and .430$_\mu$, on the vertical scale. If, for example, the luminosity of green, .520$_\mu$, increased exactly as that for red, .665$_\mu$, the result ought to give a straight line. This is so, as the upper part of the curve indicates, for the greater luminosities; but for the smaller the curve is no longer straight but curved as shown by comparing the continuous and dotted curves in the figure. The same reasoning applies to the other two colors.

These results, as well as the bulk of the measurements described in this paper, were obtained for the center of the retina. The peripheral portions of the retina, however, have their own peculiar and distinctive visual properties. The writer has obtained two curves which show some differences between the center and periphery of the retina as regards persistence of vision. The measurements were made by inclining the eye so that the flickering light fell, first, ten degrees, second, twenty degrees, from the center of the retina on the temporal side. The curves are shown in Fig. 8, in comparison with a normal curve for the center of the eye. Both curves, Nos. 2 and 3, are below the normal indicating greater sensitiveness of the retinal periphery as regards the flickerng light of all colors. Since the lowest point of the curve corresponds to the brightest point of the spectrum we see that, to the peripheral retina, the brightest light is not the yellow but the green.

It will be noticed that each peripheral curve has an elevation in the greenish-yellow part of the spectrum. The significance of this may be thus explained. In direct vision the light rays fall upon the macula lutea, or yellow spot, where the greatest distinctness of vision occurs. This spot,

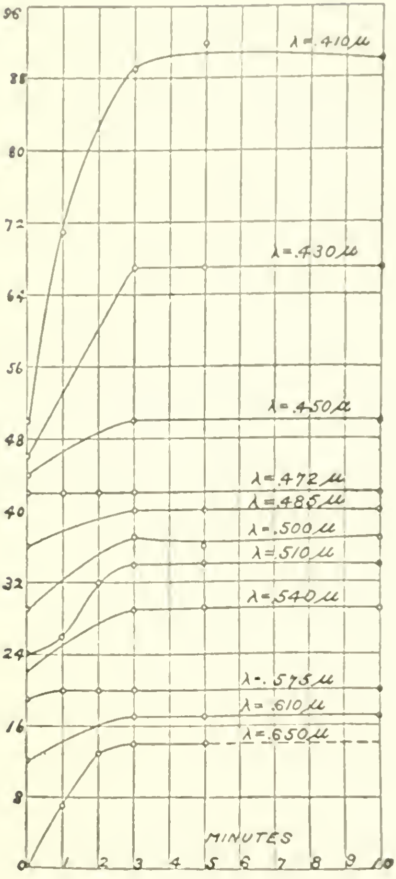


Figure 9. Persistence of Vision after Fatiguing the Eye with Various Colored Lights.

however, is small, and would not be touched by light falling on the outer regions. The macula lutea contains a yellow pigment, but no visual purple, while the retina in other parts has only this latter substance. Visual purple absorbs and is

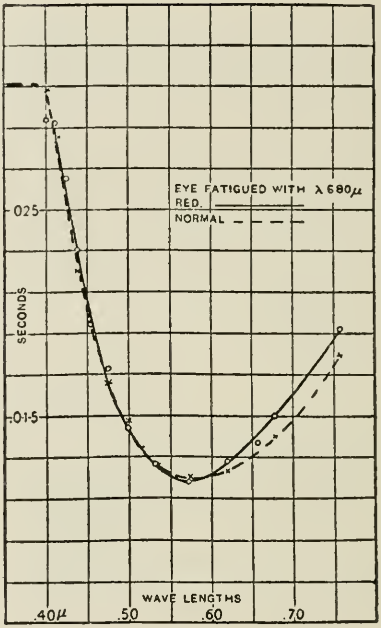


Figure 10. Retina Fatigued with
Pure Red Light.

bleached by light of all colors but in amounts varying with the wave-length, the absorption being very slight in the red and greatest in the yellowish-green, which has also the most rapid bleaching effect. The region of the spectrum, therefore, which is most absorbed by the visual purple coincides with the elevations. This shows that some of the light falling on the retinal periphery is absorbed by the visual purple and is of no service in causing vision.

We have already seen that the darkness adaptation of the retina is progressive in character. Similar studies were also made for the development of retinal fatigue when the eye was exposed to various colored lights obtained from the spectrum of an arc light. Measurements of the persistence of vision were made after fatiguing intervals of one, two, three, five and ten minutes. The results are shown in Fig. 9 for eleven different colors which are indicated on the curves. The maximum degree of fatigue is obtained in three minutes. This is two minutes less than the time required for darkness adaptation.

The normal value for each of these curves is the point where it cuts the vertical axis of the diagram for zero (o

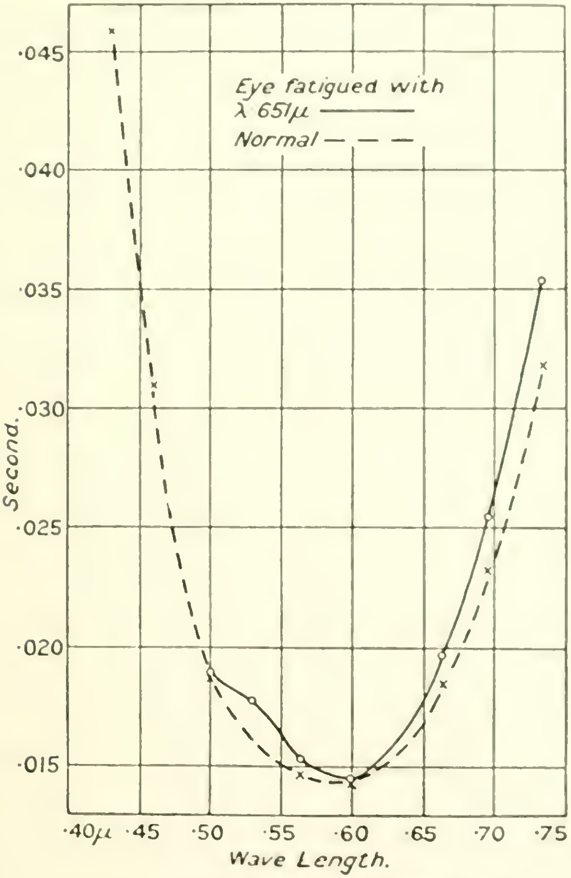


Figure 11. Retina Fatigued with Orange Light.

minutes. The interval between the lowest and highest values of the curves varies greatly, and in the case of blue, .472μ. and yellow, .575μ, it becomes zero so that these two curves are straight horizontal lines. This result indicates that, as far as the measurement of the persistence of vision is concerned, these two colors do not cause retinal fatigue. The significance of this curious phenomenon was not realized until the writer discovered the transition points in the spectrum which are now to be discussed.

A long series of persistency curves was made under the following conditions. A certain color in an arc light spectrum was isolated in a spectrometer as described above and the eye kept constantly fatigued by it. Then with the retina in this condition persistency measurements were made at intervals throughout a second spectrum. These values of the persistency were then plotted in comparison with a persistency curve made on the same spectrum with the eye in a normal condition. The places of coincidence of the two curves with, and departure from, one another give important evidence concerning the nature of the processes involved in the vision of colors.

The writer has obtained seventeen sets of these curves for the same number of different fatiguing portions of the spectrum from red to violet. By comparing these it is proved that the number of fundamental color sensations is three, viz: red, green, and violet, and the limits of wave-length between which these sensations lie are also accurately determined.

When the eye is fatigued with a pure red of wave-length, .680μ, a persistency curve is obtained which is shown by the continuous line in Fig. 10, the dotted curve being always that for the eye when in its normal conditions. The figure shows that the two curves coincide from the violet end of the spectrum to the wave-length .60μ, which is in the middle of the orange color, and then they diverge to the end of the red. In other words, fatiguing the retina with a narrow band of pure spectral red, the center of which has a wave-length of $.680_{\mu}$, affects only that process in the eye which causes the sensation of red and orange, and has no measurable effect on the green and violet processes. Precisely the same effect was obtained when the fatiguing color was $.670_{\mu}$, which is also a pure red. As the curves for these two fatiguing colors are of the same character, only one of them is reproduced here.

When the fatiguing color was $.651_{\mu}$, in the orange, which all color theorists agree is a compound sensation, the character of the curve experiences a radical change. This is shown in Fig. 11. Comparison of the two curves in this figure exhibits the same elevation in the red as in Fig. 10, and also shows an additional elevation in the part of the curve corresponding to the green region of the spectrum. Therefore when the retina is acted upon by a pure orange color, the red and the green perception processes are both fatigued, but the visual mechanism for the violet sensation is not disturbed. Persistency curves were taken also when the fatiguing colors were $.625_{\mu}$, $.620_{\mu}$, $.589_{\mu}$, and $.577_{\mu}$, all of which lie in the orange and yellow regions of the spectrum. In these four cases the curves obtained are similar to that shown in Fig 11.

Since for the red colors curves with one elevation were obtained, and also since for orange and yellow colors curves with two elevations resulted, there ought to be a fatiguing color which would mark the transition from one type to the other. Such a point was found to exist at the color whose wave-length is $.660_{\mu}$, which may be called the first transition point in the spectrum. It was discovered that four such transition points exist in the spectrum, the exact number there should be according to the three-color theory of chromatic vision.

The curve obtained for the transition color, $.660_{\mu}$, is shown in Fig. 12 and is found to have no elevations at all, but to be coincident with the normal curve throughout its length. We are justified in inferring from these curves that the colors of longer wave-length than that of the transition point, *viz:* .660μ, give rise to the sensation of pure red, and that they do not measurably affect the primary processess for green and violet colors. The fundamental red sensation must therefore lie between the red end of the spectrum and

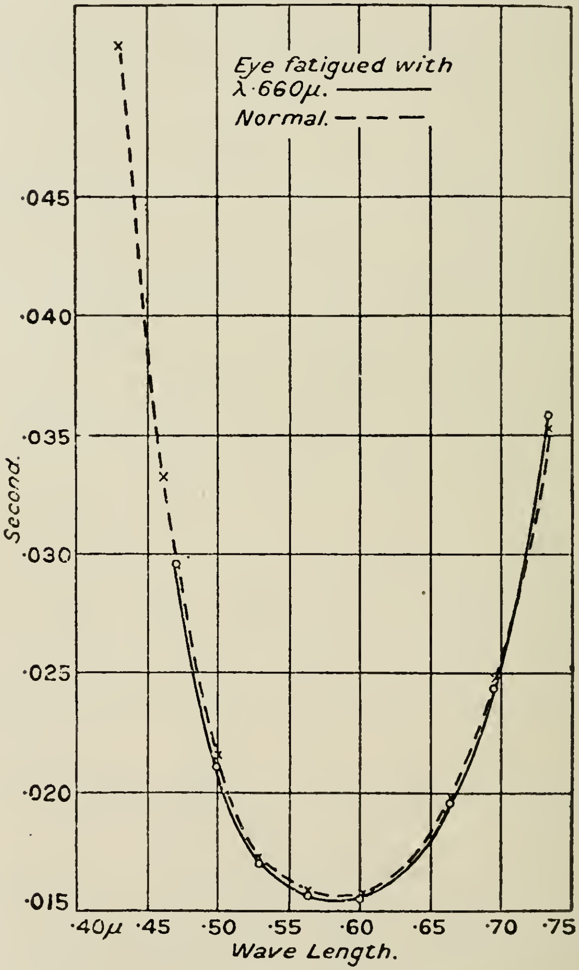


Figure 12. Retina Fatigued with a Transition Color.

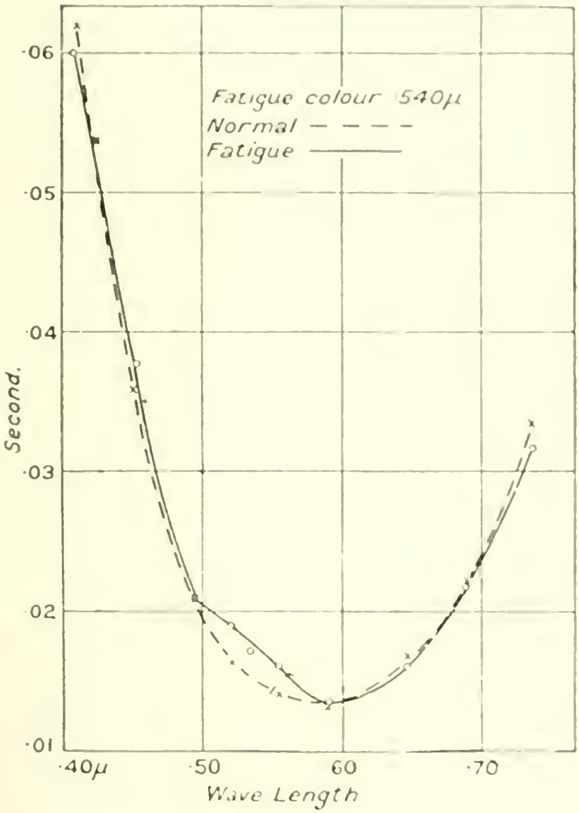


Figure 13. Retina Fatigued with Green.

the first transition point .660μ. Up to the present time the writer has found no way to determine the wave-length of the fundamental red color with any greater precision than this.

Another problem in color vision may be resolved from these curves. The cause of the sharp division of color-theorists into rival camps is largely the question as to whether yellow is a simple or a compound sensation. In purity of appearance it apparently demands recognition as a primary sensation as much as red or green. The curves for the colors .651μ, .625μ. .620μ, .589μ and .577μ, all of which lie in the orange and yellow regions, are of precisely the same character as that shown in Fig. 11. Since the yellow fatiguing colors affect the red and green sensations in the same manner and to the same degree as do the orange colors, they must be of the same fundamental nature. That is, yellow must be a compound sensation. Surely experiments like these, which any one may perform for himself, are more

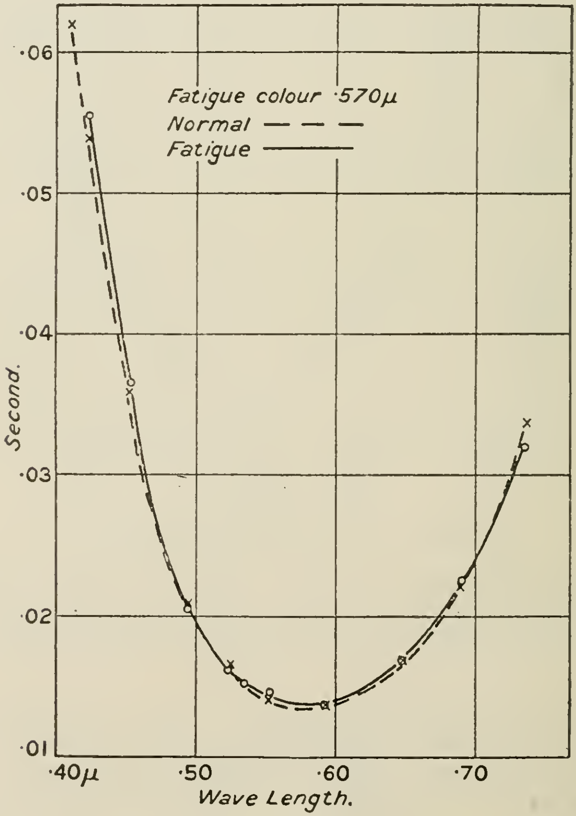


Figure 14. Retina Fatigued with a Transition Color.

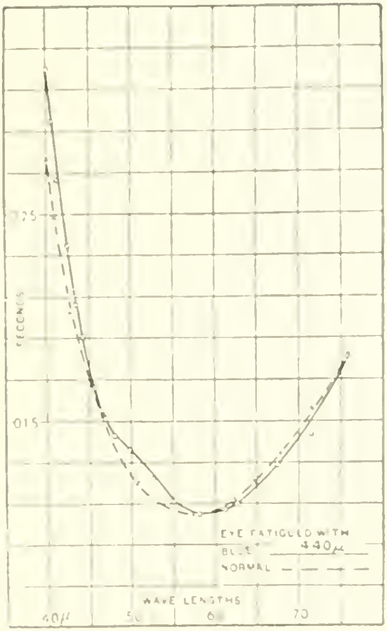


Figure 15. Retina Fatigued with a Deep-blue Color.

to be relied upon in determining the nature of the sensation of yellow than dogmatic assertions based on its mere appearance.

When the green colors .560μ, .540μ and .520μ, were used to fatigue the retina persistency curves of the same type were obtained exhibiting one elevation in the part corresponding to green, the two ends of the spectrum coinciding with the normal. This is clearly shown in that obtained for the wave-length .540μ which is exhibited in Fig. 13. When we compare the double elevation curves of the type of Fig. 11 with those of the single elevation curves of Fig. 13, it is evident that a second transition point must lie between the wave-lengths .577μ and .560μ, since the former of these has two elevations and the latter one. This second transition

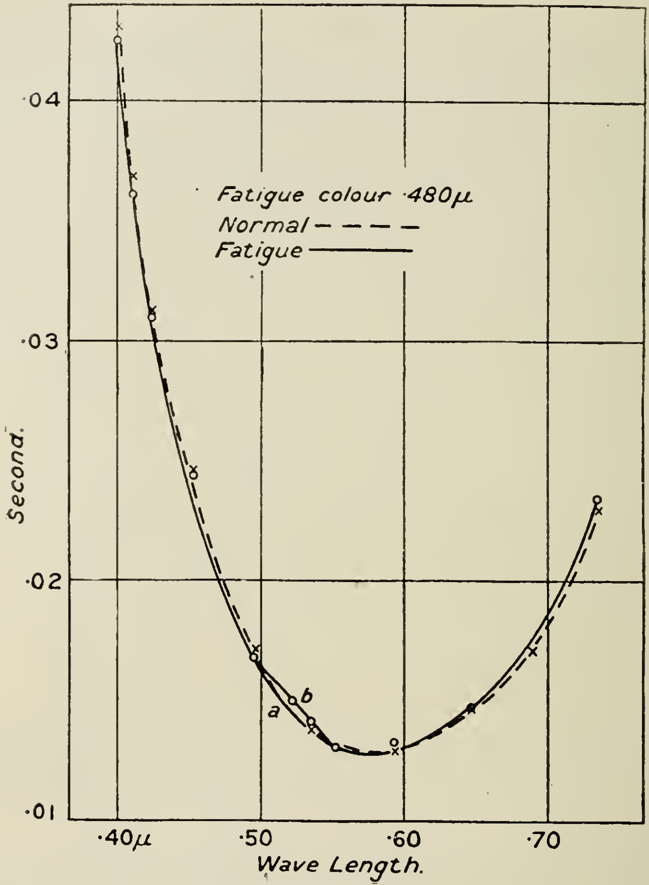


Figure 16. Retina Fatigued with Wave Length 0.480μ

point was found at the wave-length .570μ. When this was used as a fatiguing color the curve shown in Fig. 14 was obtained in which there are no elevations but coincides with the normal throughout its length in exactly the same manner as that for the first transition point shown in Fig. 12.

When the retina is fatigued with the deep blue or indigo color of wave-length .440μ a persistency curve was obtained showing two elevations, one in the green and the other in the violet. These may be seen by inspecting the curves in Fig. 15. It will also be noticed that the part of the curve corresponding to red and orange is not affected in the least degree. If we again compare the single elevation type of curve of Fig. 13 with the double elevation type of Fig. 15, it is at once clear that a third transition point must lie between the wave-lengths .520μ and .440μ. Two intermediate hues were successively used as fatiguing colors, *viz:* .480μ and .460μ. Both curves obtained are reproduced in Fig. 16 and Fig. 17, respectively. It will be seen on inspection that both curves have no elevations in either the green or the violet regions. However, the curve in Fig. 16, for the color .480μ, does show at "b" a slight vestige of the green elevation which is not at all apparent in Fig. 17. We may conclude, therefore, that the spectral region bounded by the wave-lengths .470μ and .460μ is the transition point sought for and I have accordingly designated the wave-length .470μ as the third transition point.

When the retina was fatigued with the violet of wave-length .400μ a persistency curve was obtained with but one elevation in the violet, the rest of the curve coinciding with the normal. This is shown in Fig. 18. Again, comparing this single elevation curve with Fig. 15, which is a curve of the double elevation type, it is clear that a fourth transition point must lie between them. This was found to be at the wave-length .420μ, which when used as the fatiguing color gave the persistency curve shown in Fig. 19. This shows no elevations in any part, but coincides with the normal throughout its length.

We can represent these curves in a different way so as to show them all in one figure. There is evidence to prove that the persistence of vision, or the duration of visual impressions on the retina, is dependent only on the luminosity or brightness of the color, except for very low intensities.

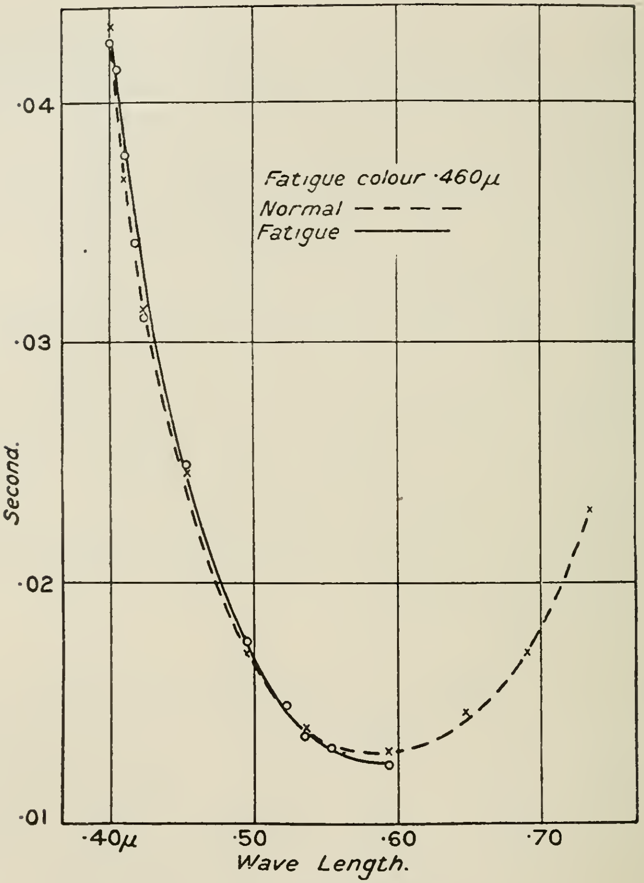


Figure 17. Retina Fatigued with Wave-Length 0.460μ.

If, therefore, the brightness of all parts of the spectrum were uniform, the persistency curve would be a straight horizontal line instead of the now familiar parabolic form. Reducing, then, the normal curve to such a horizontal straight line, and the fatigue curve in the same proportion, the relation of the two curves will be shown perhaps more clearly, especially in regard to the characteristic elevations. This has been done for the nineteen sets of curves which I have just described and they are all shown in a single figure, *viz:* Fig. 20. The wave-lengths of the fatiguing colors are indicated by the numbers on the right of the diagram and are

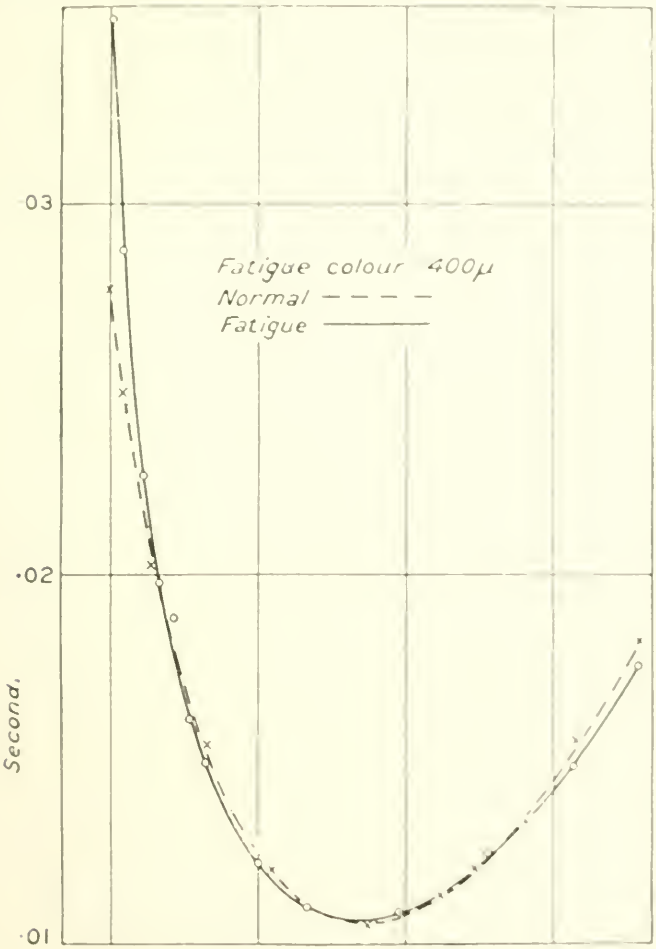


Figure 18. Retina Fatigued with Violet.

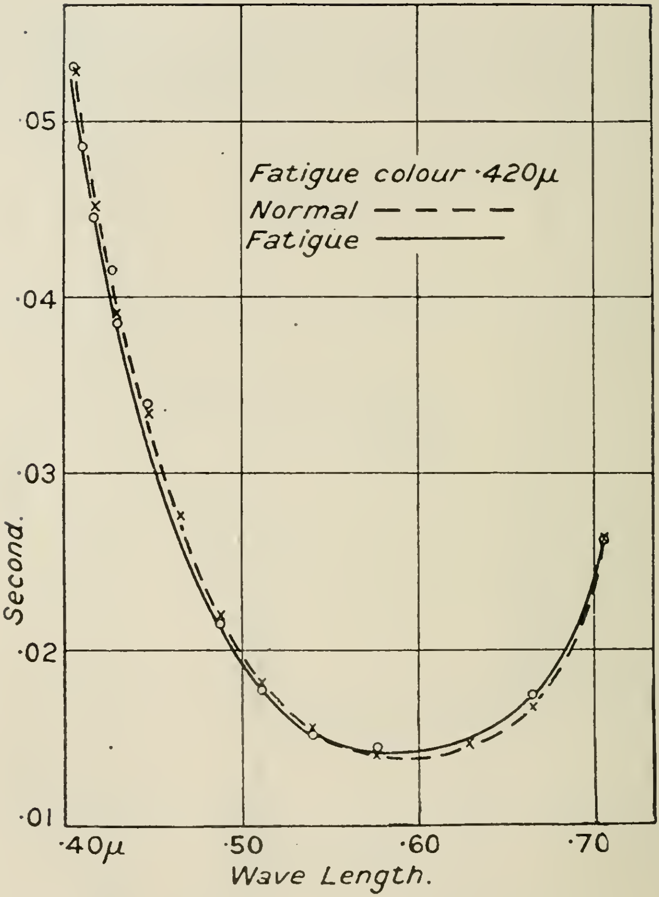


Figure 19. Retina Fatigued with a Transition Color 0.420μ.

also marked by the short vertical lines above the curves. The nature and significance of the double and single elevations, and their relation to the transition points or colors, which are marked T. P., may readily be seen. It will be noticed in particular that the elevations in all the curves occur in the parts corresponding to the red, green and violet

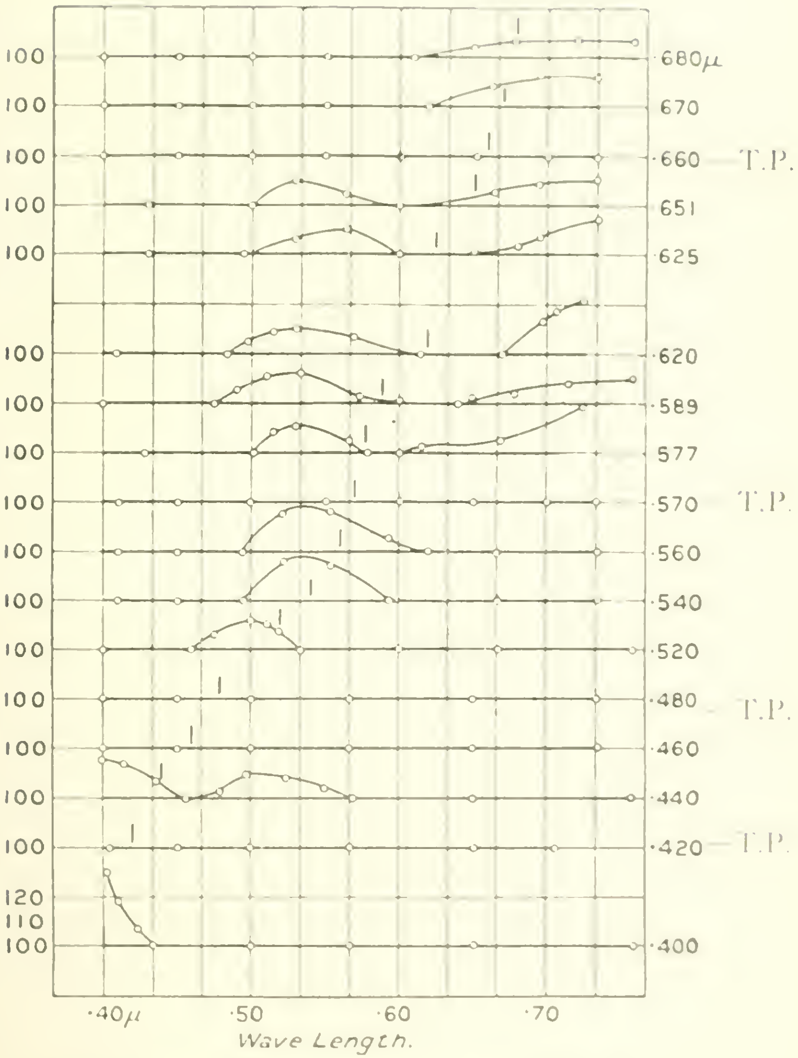


Figure 20. Relationship between the Normal Persistency Curve and the Fatigue Curve.

colors. This fact is strong evidence of the existence of three, and only three, primary sensations corresponding to those colors.

The process of compression may be carried one step further. By taking the mean values of all the elevations we may construct a single composite curve which is shown on an enlarged scale in Fig. 21. The four transition points are indicated by short vertical lines, and fall symmetrically on either side of the two minima of the curve. More conclusive evidence of the reality of the three fundamental color sensations, red, green and violet, could scarcely be desired than is afforded by the three elevations to this curve.

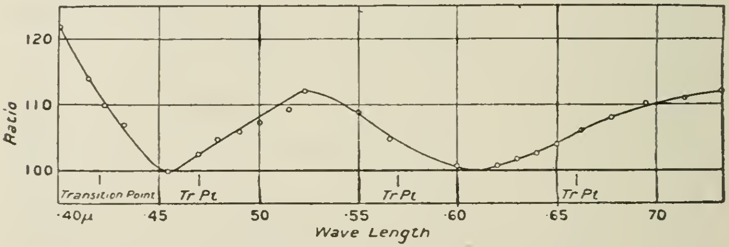


Figure 21. Illustrating Positions of Transition Points.

The general results of these experiments may be represented diagrammatically in Fig. 22. In this diagram the indicated wave-lengths mark the transition points and divide the spectrum into five parts. It is evident that the fundamental red sensation corresponds to some hue between the beginning of the red and the point of transition at .660μ. Similarly the fundamental green sensation is excited by some portion of the spectrum lying between the second and third transition points at the wave-lengths .570μ and .470μ. Finally the third fundamental sensation, which must be violet and not blue, as many color-theorists allege, lies between the fourth point of transition at .420μ and the end of the violet.

For the purpose of comparison, the writer has brought together the exact hues of the primary colors according to several investigators whose experiments were conducted on the basis of the trichromatic theory. With these are included the colors selected by Hering for his theory of color vision, and those determined for the same theory by Baird.

	Red	*Green*	*Blue*
Helmholtz	Carmine-red, not in spectrum.	.56μ to .54μ	Ultramarine Blue
Maxwell	.630μ	.528μ	.457μ
König	Purple-red; just outside spectrum.	.505μ	.470μ
Exner	Red complementary to .494μ (about .66μ)	.508μ	.475μ
Allen	Between end of spectrum and .660μ	.570μ to .470μ	Violet between .420μ and end.

	Red	*Green*	*Yellow*	*Blue*
Hering	Purple-red; non-spectral.	.495μ	.574μ	.471μ
Baird	Purple-red; non-spectral.	.490μ	.570μ	.460μ

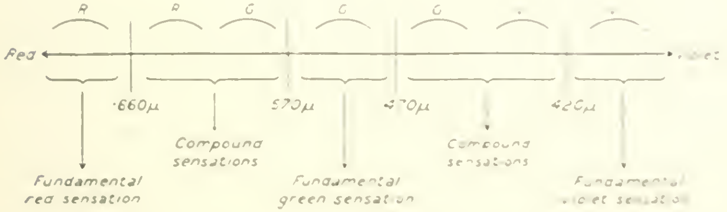

R
R
G
G
G
V
V
Red
Violet
·660μ
570μ
470μ
420μ
Compound sensations
Compound sensations
Fundamental red sensation
Fundamental green sensation
Fundamental violet sensation

Figure 22. Fundamental and Compound Sensations.

There is no conflict necessarily arising between my own fundamental hues for red and green and those of Helmholtz, Maxwell, König and Exner; there is divergence in the case of violet. But if it is at all justifiable for Helmholtz and the others to differ in their green hues by nearly .06μ, no exception need be taken to my violet determination because it differs from the others by an equal amount.

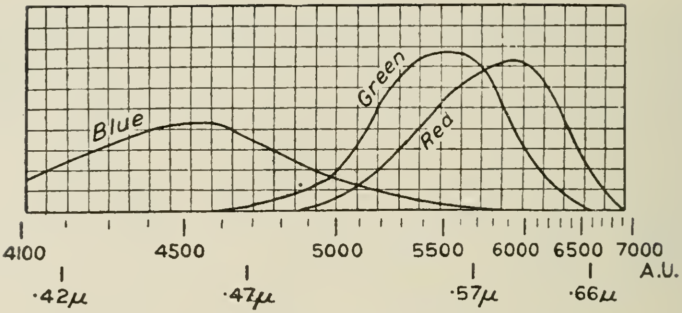


Figure 23. Normal Sensation Curves. (Abney and Watson.)

In endeavoring to connect the transition points with other color-phenomena, I have found specially suggestive the color-sensation curves of Abney and Watson, Fig. 23, and of König and Dieterici, Fig. 24. On each of these figures I have indicated the transition points by short vertical lines with wave-lengths attached. The meaning of these sensation curves is that the sensation excited by any given wave-length of the spectrum is really made up of a combination of red, green, and blue or violet sensations in proportion to the ordinates of the curves at the given wave-length.

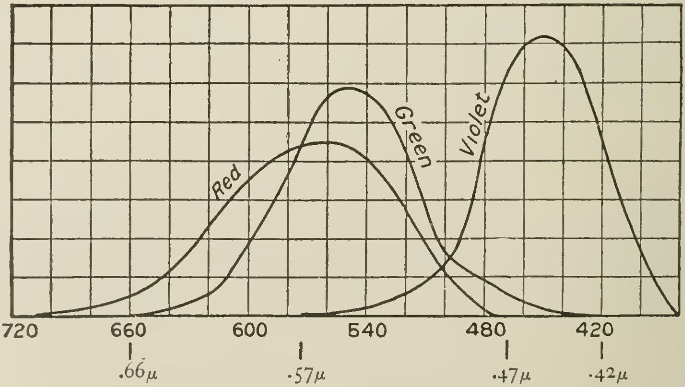


Figure 24. Sensation Curves. (König and Dieterici.)

In the curves of Abney and Watson the transition points .660μ and .470μ are practically at the ends of the sensation curve for green; and the other transition points at .420μ and .570μ are near the ends of the sensation curve for blue. The transition point at .570μ is also very close to the intersection of the green and red sensation curves. The transition point at .420μ is shown by the curves to be practically outside the influence of the red and green sensations, and hence may be regarded as a region of a single pure color sensation. Similarly, the spectral region from the transition point .660μ to the end of the spectrum is pure red free from the influence of the other two sensations.

The sensation curves of König and Dieterici, Fig. 24, show some differences. The ends of the green sensation curve are the transition points .660μ and .420μ, while the transition point .470μ is still the more refrangible end of the sensation curve for red. The transition point .570μ marks one end of the sensation curve for violet. It will be noticed that the regions between the transition points .660μ and .420μ and the respective ends of the spectrum are, as before, characterized by purity and simplicity of color sensation. The transition point .570μ is again at the intersection of the red and green sensation curves, that is, where the two sensations balance the influence of each other, without sufficient of the third sensation to make itself perceptible. In both figures one can see reasons why the regions between .420μ and .470μ, and between .570μ and .660μ should be characterized by compound sensations. But it is difficult to understand why the exceedingly complex region between .470μ and .570μ should exhibit, as it does, persistency curves with only one elevation in the green.

The general conclusions regarding the color sensations which we have now reached are greatly strengthened by the study of natural color-blindness. Since we have proved the fundamental sensations to be red, green and violet, we may anticipate the possible types of color blindness. In general there may be: three types in which *one* sensation is missing; three types in which *two* sensations are missing, and one type in which *three* sensations are missing; that is, there are seven possible types of color-blindness. We may represent them as follows:

Red-blindness.
Green-blindness.
Violet-blindness.
Red-Green-blindness.
Red-Violet-blindness.
Green-Violet-blindness.
Red-Green-Violet-blindness.

Some years ago I made a close study of color-blindness and determined the persistency curves of about twenty-six cases. Among them I found no less than six out of the seven possible types, the only type I did not discover being violet-blindness. These curves are all reproduced in Plates I, II and III, and the classes to which the individual curves belong are indicated on the curves in accordance with the following classification.

Class I	Red-blindness.
Class II	Green-blindness.
Class III	Red-Green blindness—Two varieties.
Class IV	
Class V	Red-Violet blindness.
Class VI	Green-Violet blindness.
Class VII	Red-Green-Violet-blindness; or total color blindness.

Since Classes III and IV are really two subdivisions of the same general type, the seven classes include only six types. These persistency curves for color-blindness bear a remarkable resemblance to those which we have studied for retinal fatigue, which is thus seen to be analogous to artificial or induced color-blindness.

As far as we may conclude from these cases the most common types of color-blindness are: red-blindness, red-green blindness and red-violet blindness, which together comprise

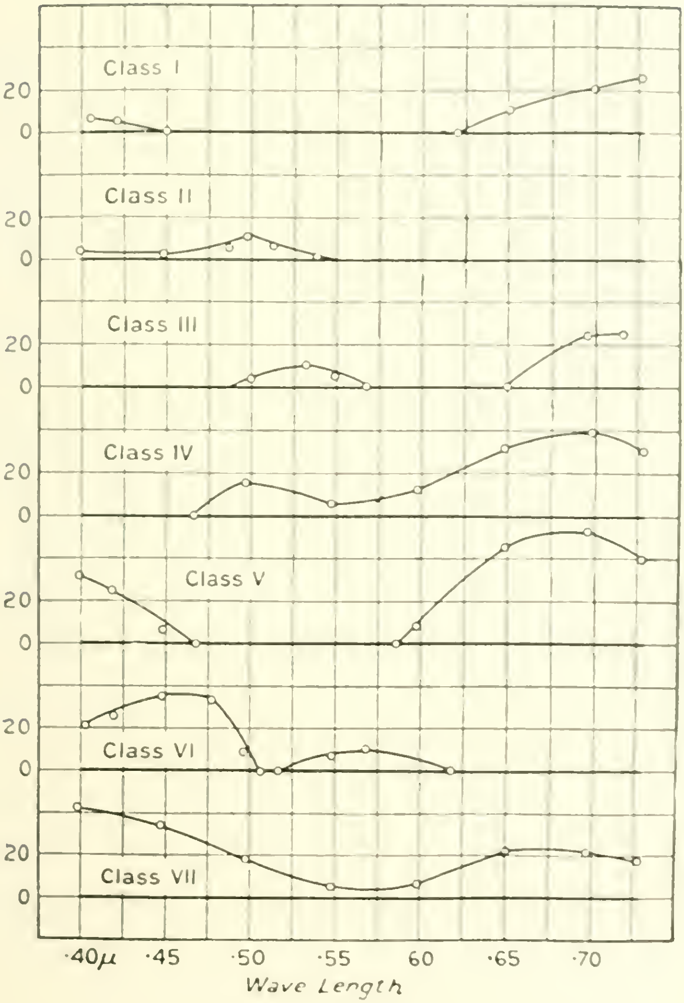


Figure 25. Departures of Persistency Curves of Color-blind Persons from the Normal Persistency Curve.

twenty out of the twenty-six cases studied. Some of the other types are evidently distinctly rare.

Typical examples of these curves are shown also on the single diagram plan in Fig. 25, which exhibits the characteristic elevations in the clearest manner. It will be of advantage to compare this figure with the curves in Fig. 20 which is described above. These curves for color-blindness confirm in the strongest and clearest manner the conclusions already reached from the experiments on normal eye regarding the number and designation of the fundamental color sensation.

One further problen in color vision may be fittingly referred to in concluding this paper. On one occasion I fatigued

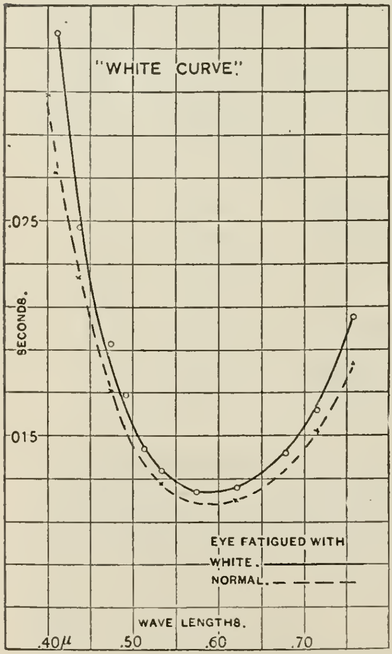


Figure 26. Persistency Curve after Fatiguing with White Light.

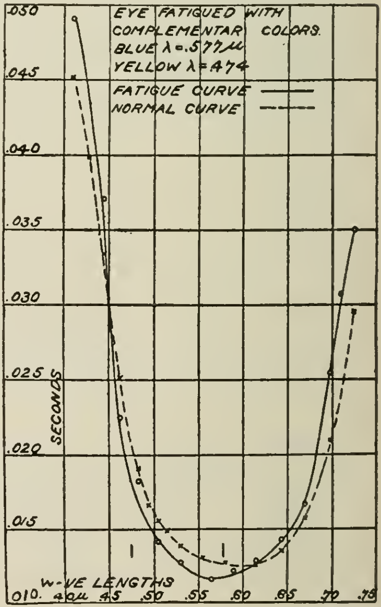


Figure 27. Persistency Curve of the Eye Fatigued with Complementary Colors, Blue and Yellow.

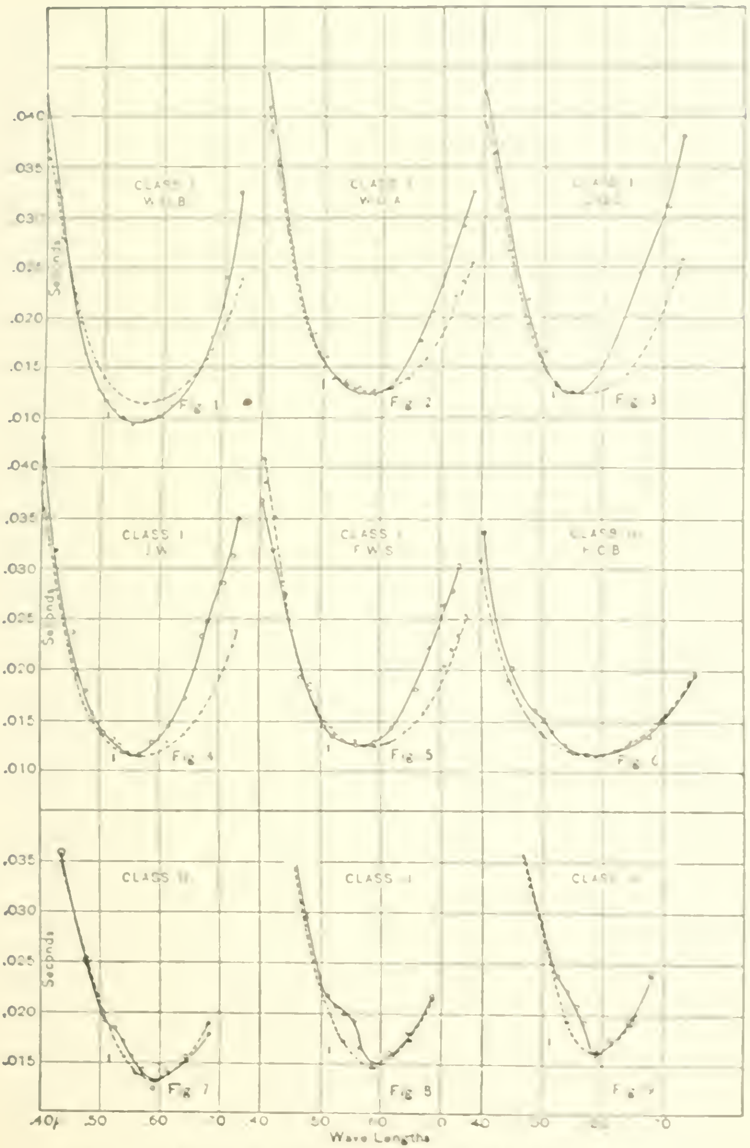


Plate I. Classes of Persistency Curves of Color Blindness

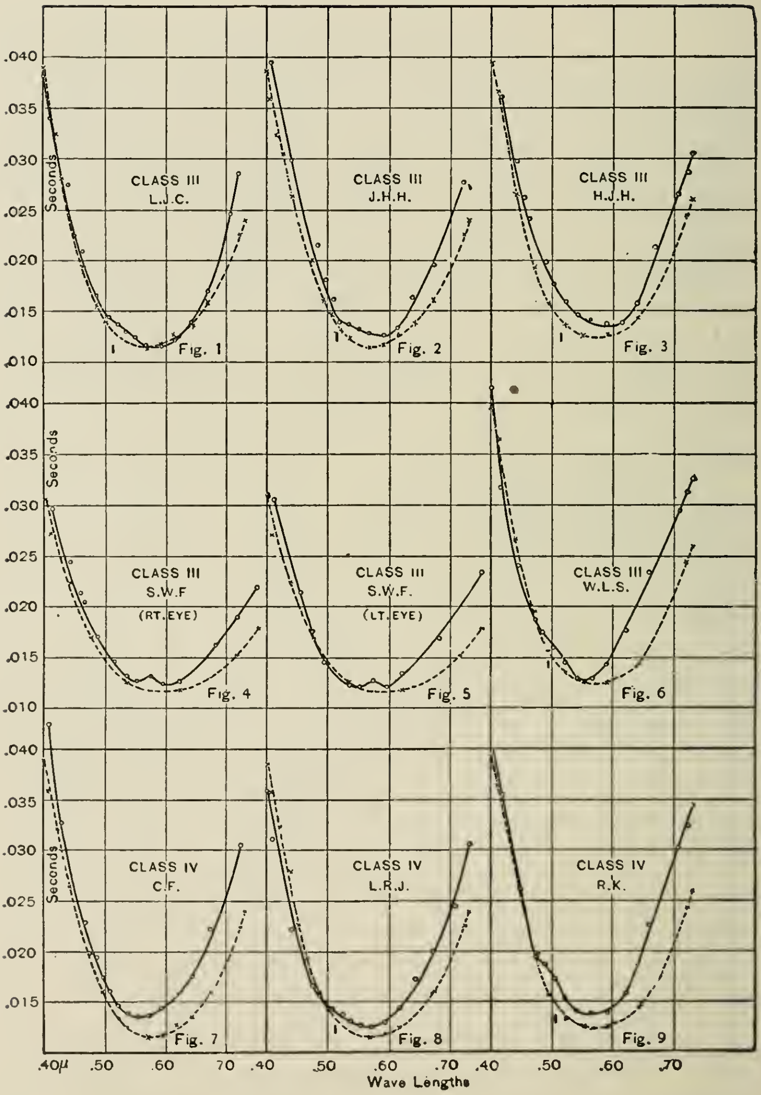


Plate II. Classes of Persistency Curves of Color-blindness.

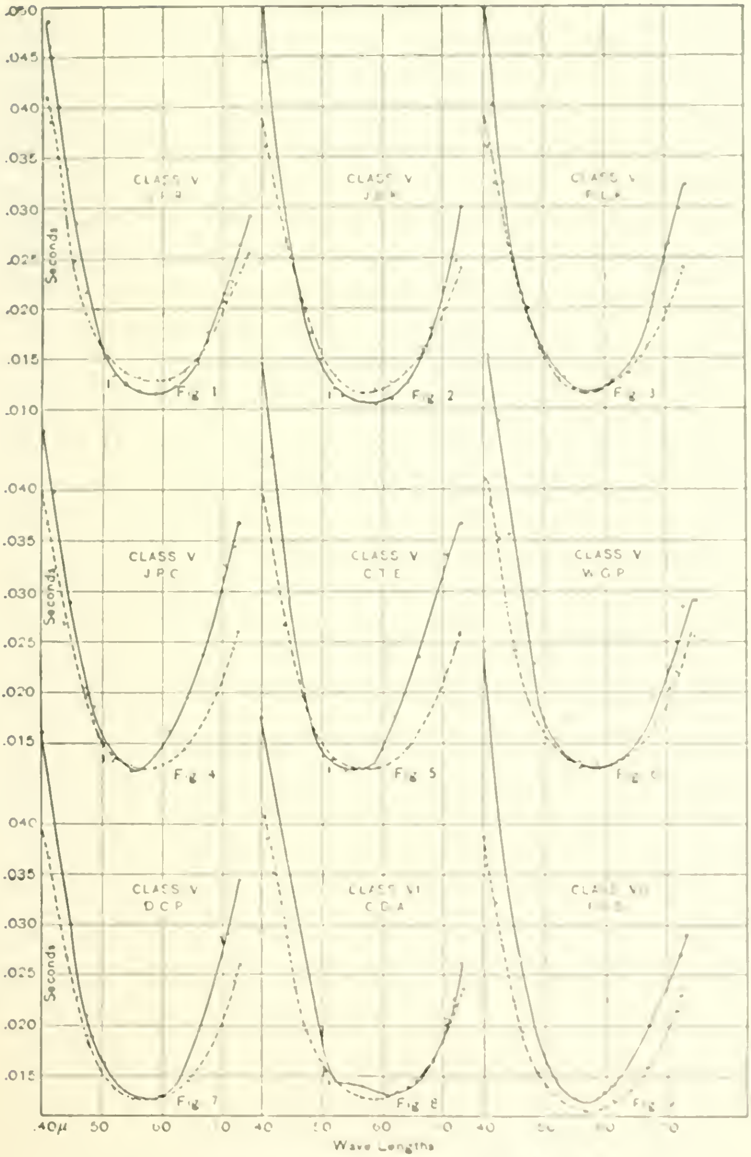


Plate III. Classes of Persistency Curves of Color Blindness

my eye with white light from an electric arc and obtained the persistency curve shown in Fig. 26. In this, the whole fatigue curve is elevated above the normal. This it will be observed is exactly like the one obtained by a totally color-blind person and shown in Plate III, Fig. 9, Class VII. As white light, indistinguishable from ordinary white, may be obtained by mixing two complementary colored lights, observations of the persistence of vision were made after fatiguing the retina with proper combinations of colors.

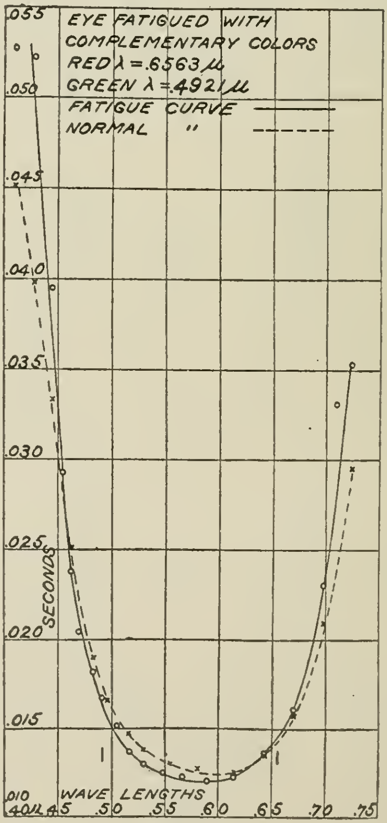


Figure 28. Persistency Curve of the Eye Fatigued with Complementary Colors, Red and Green.

Two overlapping spectra were formed in a color mixing spectrometer and the selected complementaries combined in a shutter eyepiece. The intensities of the two component colors were adjusted so as to give a pure white light. The first pair of complementaries used were yellow $.577\mu$ and blue $.474\mu$ as determined by Von Kries. The second pair were red $.656\mu$ and green $.492\mu$ as determined by Helmholtz. The persistency curve for the former pair is shown in Fig. 27 and that for the latter in Fig. 28.

On comparing the figures both curves are seen to be essentially the same and also to differ greatly from the white fatigue curve of Fig. 26. Instead of the whole of the complementary color curves being elevated above the normal, the part corresponding to green is actually depressed below the normal. They bear in fact a close resemblance to the curves obtained for the cases of red-violet blindness shown in Plate III, Class V.

The effect on the retina of white light of the comparatively few wave-lengths comprised in the complementary colors must of necessity be different from that of the complex mixture of waves forming the white light from an electric arc. The psychological effect of the two kinds of white light is precisely the same; yet measurements of the persistence of vision are capable of showing in a most striking manner the differences in the physiological effects of the two lights on the retina.

This is the extent to which my researches on color vision have at present carried me. It is evident that much interesting information regarding the retinal processes excited by the vision of colors is yet awaiting discovery, and no doubt this method will be of great service to that end.

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ON REFLEX VISUAL SENSATIONS AND COLOR CONTRAST

By

Frank Allen

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SYNOPSIS

Section I. In this section experiments are described in which spectral colors of known wave lengths are allowed to fall on one side of the vertical median line of the right retina, and the reflex enhancement of all parts of the spectrum are measured for the contiguous area on the other side of the retina. It is shown that reflex enhancement of the red, green, and violet colors is produced, but that the predominant enhancement is in the portions of the spectrum complementary to the active color. The six equilibrium colors produce no effect.

When white light and darkness are used instead of colors, enhancement of the whole spectrum results. Darkness on the reflex area diminishes the brightness of the whole spectrum. It was found also that the black interior of the eyepiece of the observing spectrometer had an important effect which must be taken into account. Numerous curves are plotted from the measurements which show the effects obtained with each color.

Section II contains the theoretical discussion of the results, and explanations are offered for colored shadows, for simultaneous color contrast under various conditions, for luminosity contrast, and for successive contrast.

It is shown that the explanation of contrast is physiological and not psychological, though the nature of the visual reflex renders necessary the operation of the visual centres of the brain.

Certain deductions are made regarding the probable non-contrasting peculiarities of equilibrium colors.

I. Experimental

Simultaneous contrast or spatial induction of colors has long remained one of the great outstanding difficulties in formulating an acceptable theory of color vision. Notwithstanding prolonged observation and study it has been found impossible to decide conclusively whether the phenomena have their origin in the physiological processes of the retina or in the psychological operations of the visual centres.

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*Read at the meeting of the Royal Society of Canada, Ottawa, May, 1923. Also at the meeting of the Optical Society of America, Cleveland, Oct., 1923.

Color theorists consequently have adopted widely divergent opinions on the vexed question. Peddie,[1] in his recent work, believes the three component theory of Young to be so completely and securely established that it makes no difference which explanation is correct, the physiological or the psychological, rather indifferently remarking that "the question is merely one of fact." Greatly differing from this is Hartridge's[2] acceptance of the psychological explanation coupled with the further opinion that failure to account for the phenomena of contrast is no reproach to any theory of color vision, inasmuch as two theories are necessary, one for the purely retinal or peripheral processes, and a second for the central or psychological. "We need not, however," he says, "go further into these matters because it is now established, almost beyond dispute, that while colour vision depends on peripheral analysis, i.e. in the retina, simultaneous and successive contrast are due to processes of central origin, i.e. in the brain. It is not therefore necessary for any hypothesis which is supposed to represent the peripheral processes to offer an explanation of contrast as well."

By using the expression "spatial induction" for the traditional term "simultaneous contrast," Parsons[3] appears to regard the phenomena as physiological in their origin.

It can scarcely be doubted, however, that in establishing a correct theory of color vision it is of fundamental importance to prove beyond question whether contrast, both color and luminosity, is physiological or psychological in its nature. For especially if it is the former, the establishment of that fact is altogether likely to suggest additional phenomena which may throw light upon the whole process of color vision.

In a recent communication[4] on 'Reflex Visual Sensations' it was shown by the writer, with an abundance of experimental verification, that every ray of light produced upon the retina two general effects, a direct and a reflex. The direct action fatigued either one or two of the primary sensations, red, green, and violet, according as the color stimulus was simple or compound in its nature; the reflex effect caused the excitation of all three sensations in such a manner as to enhance their luminous response. It was further indicated that this reflex action was responsible for the production of the white light underlying all sensation of color, and that this light was also to be identified with the self light of the retina, which is white, or possibly yellowish, in tone.[5]

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[1] Colour Vision, p. 21.

[2] Brit. Jour. Ophthal., March, 1923.

[3] Colour Vision, p. 125.

[4] J. O. S. A. & R. S. I., p. 583, 1923.

The reflex effect was found to be transferred from one eye to the other; or, if both were to be regarded as transferable, the reflex was always greatly in excess of the direct. In the case of six colors it was also found that the direct and reflex effects balanced or neutralized each other, so that even after prolonged exposure of the eye to their influence, all colors of the spectrum were seen without diminution or enhancement of brightness. In consequence these hues were termed equilibrium colors.

Since darkness adaptation of one eye was found strongly to affect the other, the experiments were conducted in a room illuminated with ordinary daylight, so that the unused eye was maintained in daylight adaptation.

These discoveries suggested that probably the reflex effects of color stimulation might also be transferred from one area of a retina to adjoining regions, and thereby afford a definite physiological explanation of the modification of the appearance of two adjacent light or colored areas by the reflex influence of each upon the other.

The most convenient as well as the most obvious method of studying this application of reflex sensations was to fatigue an area of the retina on one side of the vertical median line, and to measure the duration of the flashes of light at the critical frequency of flicker on the contiguous area on the other side.

For this purpose a normal curve was first necessary as a standard of comparison. The normal curve in the previous investigation[6] was obtained for the central part of the retina including areas on both sides of the median line. New measurements were made with the same apparatus and adjustments as were used before. The right eye was fixated on a small dust particle adhering to the edge of the shutter on the *right* side of the rectangular patch of color in the spectrometer with which the measurements were made. The patch of color was thus viewed by slight indirect vision. It was found that the new measurements coincided with the normal curve previously obtained, which is therefore reproduced here from the former paper. The data are given in Table 1.

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[5] Peddie: Colour Vision, p. 81.

[6] J. O. S. A. & R. S. I., p. 587, 1923.

The adjoining retinal area was then fatigued by fixating vision on a conveniently situated particle on the edge of the shutter on the *left* side of the fatiguing rectangle of color in a second spectrometer with which an electric arc was employed as the source of light. By this method, fatigue could be confined to one retinal area, and the reflex effects,—and the direct if any—transferred to the adjacent area, could be investigated.

This method of study is extremely well adapted for investigating these transferable effects. For if the curves obtained under the conditions just described always coincided with the normal, it could safely be inferred that no effect, either direct or reflex, measureable by this method, was transferred from the fatigued to the observing area. Since, also, in the normal eye fatigue invariably shows itself by producing a diminution of the physiological brightness of either one or two spectral regions, causing corresponding elevations above the normal, it could readily be ascertained from a comparison of the curves whether the direct effect of fatigue was similarly transferred. Finally, if the curves showed depressions below the normal, it would then be proved that color and light impressions produced reflex effects upon contiguous areas.

TABLE 1. *Color Contrast*

λ	Normal	.676μ	.660μ	.588μ	.572μ	.569μ	.545μ	.450μ	.410μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.750μ	0.0360	0.0344	0.0353	0.0336	0.0364	0.0349	0.0342	0.0340	0.0335
.740	.0335	.0311	.0329	.0308	.0338	.0326	———	.0315	.0315
.720	.0287	.0266	———	.0271	.0291	———	.0274	———	———
.700	.0244	.0224	.0240	.0229	.0245	.0237	.0231	.0229	.0231
.680	———	.0190	———	.0196	———	———	———	———	———
.660	.0174	.0166	.0178	.0164	.0172	.0166	.0166	.0169	.0173
.640	———	.0156	———	.0147	———	———	———	———	———
.620	.0152	.0145	.0153	.0138	.0152	.0145	.0147	.0150	.0145
.590	.0148	.0140	.0150	.0134	.0145	.0142	.0141	.0141	.0140
.550	.0155	.0147	.0154	.0140	.0153	.0150	.0148	.0147	.0142
.530	.0165	.0157	———	.0151	———	———	———	.0158	.0154
.500	.0209	.0202	.0205	.0198	.0202	.0197	.0204	.0206	.0193
.480	.0255	.0247	———	.0241	———	———	———	———	———
.450	.0336	.0334	.0338	.0319	.0342	.0330	.0324	.0321	.0309
.433	———	.0378	.0391	.0370	.0404	.0376	.0369	.0365	.0355
.420	.0431	.0412	.0426	.0413	.0434	.0424	.0418	.0411	.0390
.410	.0459	.0439	———	.0437	———	———	———	———	———

The first color used for fatiguing purposes was red of wave length .676μ. The measurements obtained are given in Table 1, together with similar measurements for all the full color curves discussed in this paper. The curve is shown in Fig. 1 in comparison with the normal. The presence of three reflex depressions proves that the effect of the active color falling upon one side of the retina was transferred to the adjoining area by reflex action and not by direct. The curve shows that red light has affected the three sensations red, green, and violet, enhancing the perception of those colors. The curves approach each other closely at the wave lengths .47μ and .65μ, which were termed coincidence points. Only one curve was obtained for red, and for each general color.

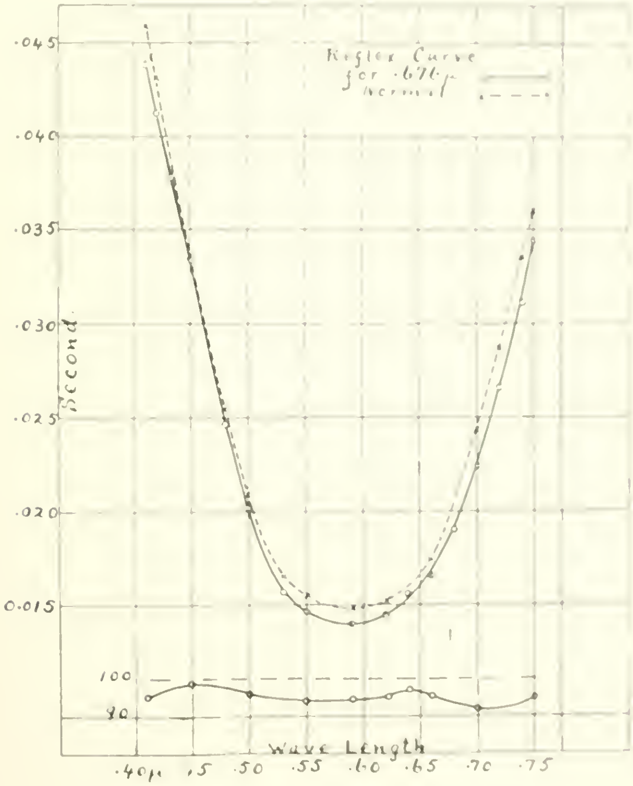

Fig. 1.—Reflex Curve for .670μ

It was anticipated that the equilibrium color .660μ would have no effect either in diminishing or enhancing color perception. In Fig. 2 the curve is shown which coincides with the normal throughout its length.

Only one color for yellow and orange was used, that selected being .588μ. As the curve in Fig. 3 shows, this color caused two reflex depressions, the larger extending from the red to the wave length .50μ, and a smaller from there to the end of the violet. The larger shows some evidence of division into two smaller parts at the wave length .68μ.

The second equilibrium color .570μ was then used to fatigue the eye. After the measurements had been made the setting of the spectrometer was reëxamined and found to be .569μ. The data in the table are therefore for this latter color. The curve in Fig. 4 shows depressions though not very clearly differentiated into three parts. Readings for the exact color .570μ were made for a few points in the middle of the spectrum, but depressions were always shown. Finally the wave length .572μ was employed as the active color, and, as the corresponding curve in Fig. 5 shows, produced no depressions, and therefore may be regarded

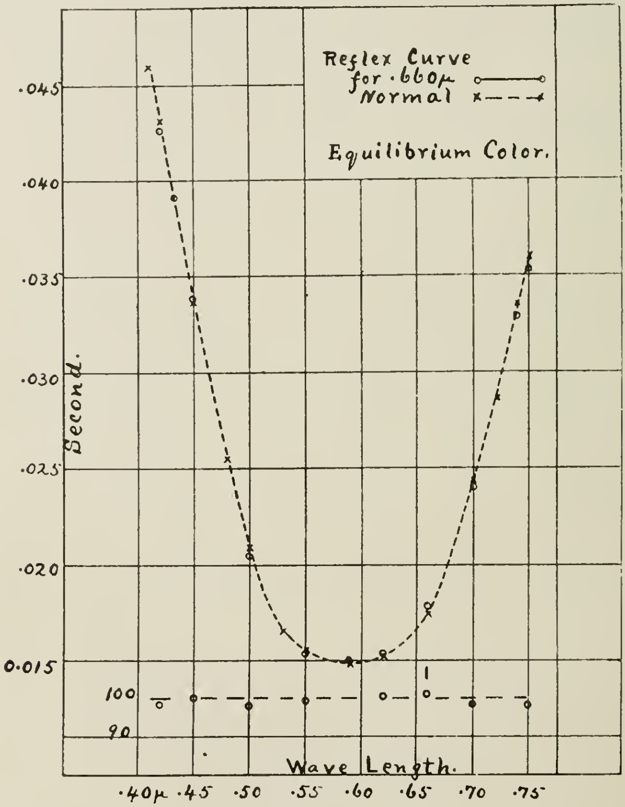

FIG. 2. *Reflex Curve for .660μ.*

as the equilibrium color. Previous determinations of this equilibrium point appeared to fix it quite accurately at .570μ, but the particular wave length .572μ given here may be a little more exact. Abney and König found that their sensation curves[7] for red and green intersected at .577μ and .573μ, respectively; and this new determination

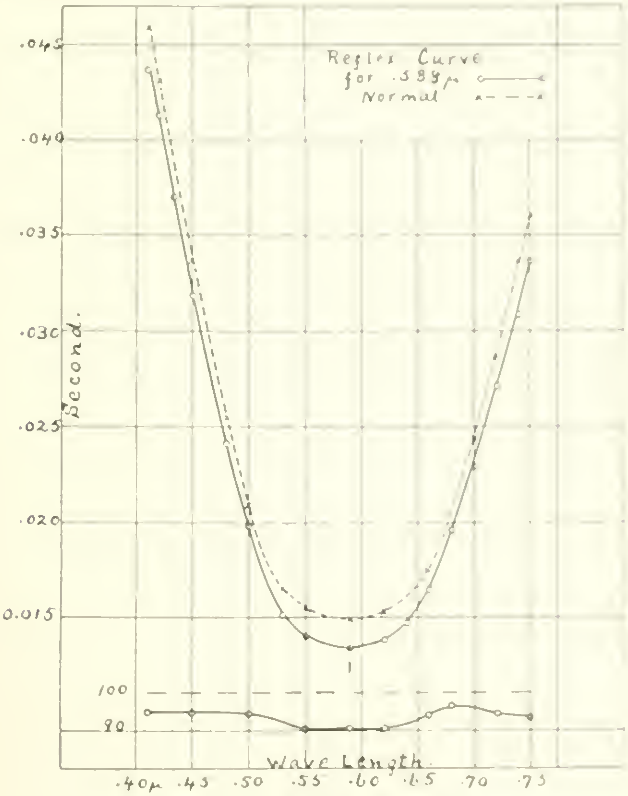

Fig. 3. *Reflex Curve for 588μ*

Table 2. *Color Contrast. Partial Curves*

λ	Normal	660μ	588μ	569μ	572μ	574μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
660μ	0.0174	0.0178	0.0164	0.0166	0.0172	0.0168
620	.0152	.0153	.0138	.0145	.0152	.0147
590	.0148	.0150	.0134	.0142	.0145	.0143
550	.0155	.0154	.0140	.0150	.0153	.0149
530	.0165	——	.0151	——	——	——
500	.0209	.0205	.0198	.0197	.0202	.0202

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[7] Parsons: Colour Vision, p. 230.

of the equilibrium color serves at least to bring it very closely in harmony with the latter.

From the data in Table 2 the central portions of several curves are given in Fig. 6 which indicate clearly the definiteness as well as the narrowness of the equilibrium region.

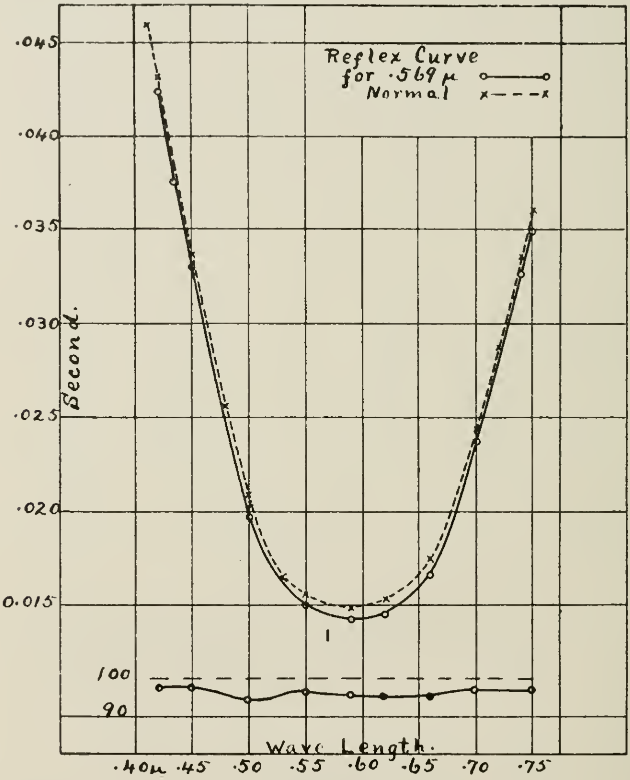

FIG. 4. *Reflex Curve for .569μ.*

The color .545μ was then used as the fatiguing stimulus with the result shown in Fig. 7. This curve shows three small depressions separated by the coincidence points at about .50μ and .65μ.

The visually complex part of the spectrum from .520μ to .480μ was studied by obtaining the central portions of the curves. The measurements are shown in Table 3, and the curves are all plotted in Fig. 8. It will be seen that the equilibrium colors .520μ, .505μ, and .480μ, do not give rise to any transferable effects, since no enhancement of brightness results.

Only one color in the blue was used as the fatiguing stimulus, that selected being .450μ, the curve for which is shown in Fig. 9. This is characterized by three well marked depressions.

TABLE 5. *Color Contrast. Partial Curve*

λ	Normal	545μ	520μ	515μ	505μ	495μ	480μ	450μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
660μ	0.0174	0.0166	0.0174	0.0169	0.0174	0.0176	0.0171	0.0169
620	.0152	.0147	.0154	.0149	.0150	.0151	.0154	.0150
590	.0148	.0141	.0145	.0142	.0147	.0144	.0147	.0141
550	.0155	.0148	.0152	.0147	.0151	.0147	.0155	.0147
530	.0165	——	——	——	.0161	.0157	.0163	.0158
500	.0209	.0204	.0203	.0196	.0203	.0204	.0205	.0206

The equilibrium color .425μ was found to give a curve coincident with the normal similar to that in Fig. 2.

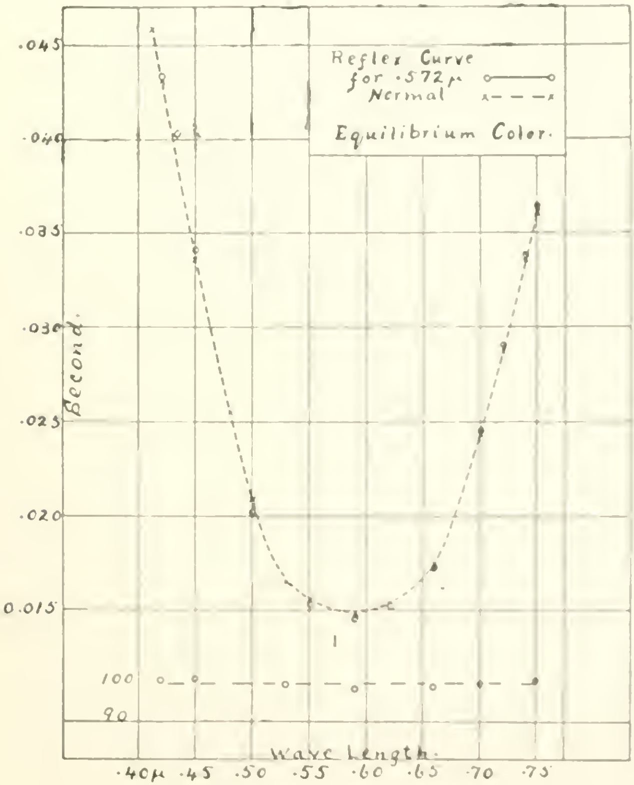

FIG. 5. *Reflex Curve for .572μ.*

The violet color .410μ, as is shown in Fig. 10, gave two reflexes, the larger of which is partly subdivided into two smaller depressions at the 'coincidence point,' about .51μ. Considering the very low intensity of this color, about one seven-hundredth of the brightness of yellow, its reflexes are the greatest of all.

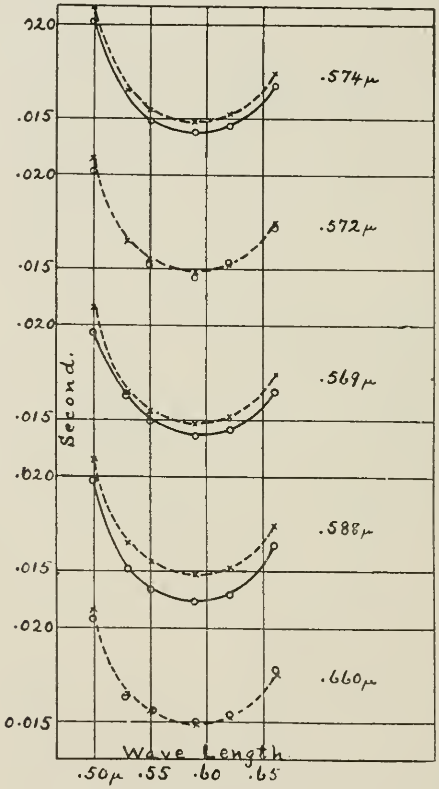

FIG. 6. *Partial reflex curves for colors indicated.*

The remarkable character of the equilibrium colors is shown in three ways. First, they produce no action transferable from one eye to the other;[8] second, they show no effect on the fatigued area of a retina;[9] third, they produce no transferable effect from one area to another on a single retina.

The reflex depressions generally were not as large nor as sharply defined as expected, and are considerably smaller than similar reflexes obtained in the right eye from the action of colors on the left as described in the former paper on reflex visual sensations to which reference has just been made.

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[8] J. O. S. A. & R. S. I., p. 585, 1923.

[9] Ibid: p. 600.

Though it ought to have been evident at first, it was not realized by the writer until most of the curves had been obtained, that when vision was fixated on the edge of the bright fatiguing patch of color, the retina was really not under one but under two influences. On one side of the retina was the active fatiguing color, and on the other darkness due to the black shutter. The retinal area in which the reflexes were obtained and studied was consequently under the neutralizing effect of darkness adaptation. This, as the previous investigation showed,[10] and confirmed in several subsequent figures in this paper, has the effect of wholly or partially counteracting the reflex enhancement of the color sensations. In the preceding curves the reflexes are not completely

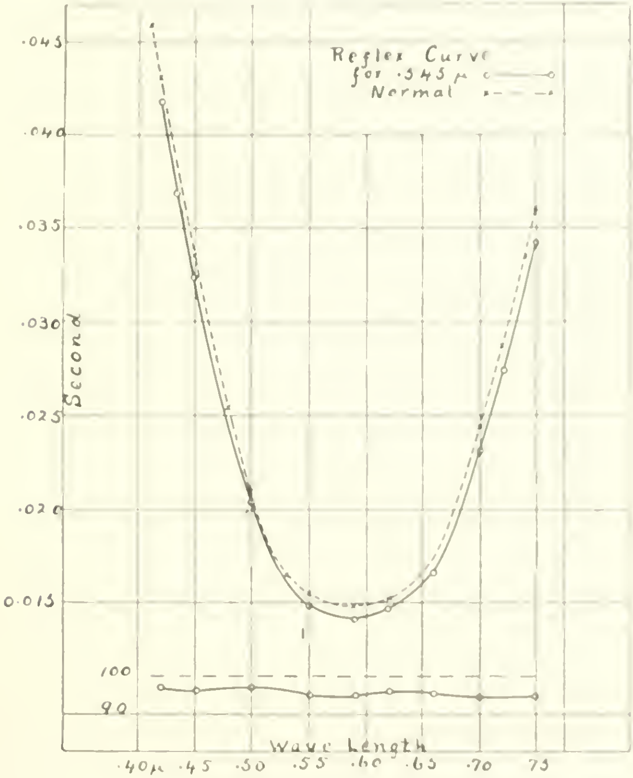

FIG. 7. *Reflex curve for .545μ.*

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[10] Ibid: p. 608.

neutralized, but the depressions are not as deep as they should be to give a just representation of the reflex effect of the active color.

In order to test this experimentally, a piece of white paper was placed on the left shutter in the Hilger eyepiece of the fatiguing spectrometer, and illuminated by reflecting daylight upon it through a hole in the top. The first measurements made under these conditions showed a smaller reflex than that obtained with the dark shutter. From this it was evident that the white light reflected from the paper was so dim that it was much more effective than complete darkness in counteracting the reflex effects of color. This was quite in accordance with what was previously found[11] in the investigation of the effect of weak light upon the perception of color.

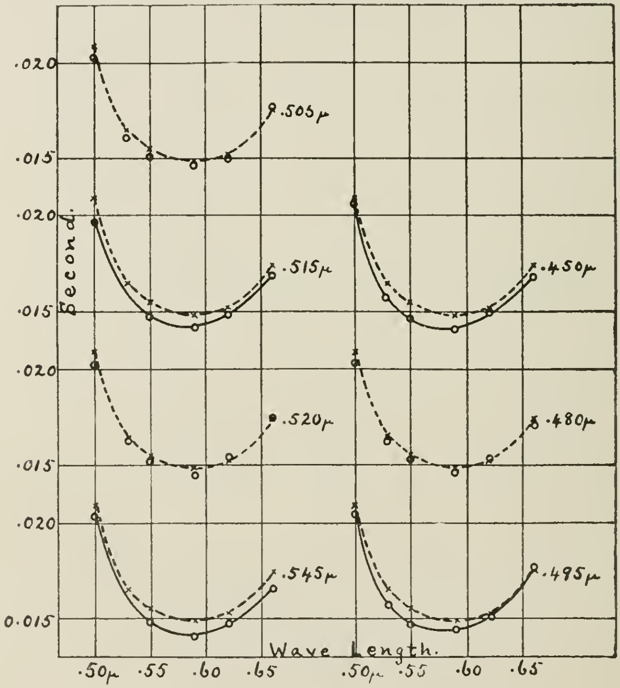

FIG. 8. *Partial reflex curves for colors indicated.*

By means of mirrors the intensity of the daylight reflected from the white paper was considerably increased, and the green-yellow reflex again measured and found to be doubled in depth.

These effects were studied only for the central part of the spectrum with the two fatiguing colors .687μ and .450μ. The results are given in

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[11] Ibid. p. 608.

Tables 4 and 5, and the curves are shown in Figs. 11 and 12, respectively, on a somewhat larger vertical scale than that in the other figures. In both figures, A, is the normal curve, B, the reflex curve obtained for adaptation with dim white light; C, the reflex curve obtained with darkness adaptation; and D, the reflex curve obtained with daylight adaptation.

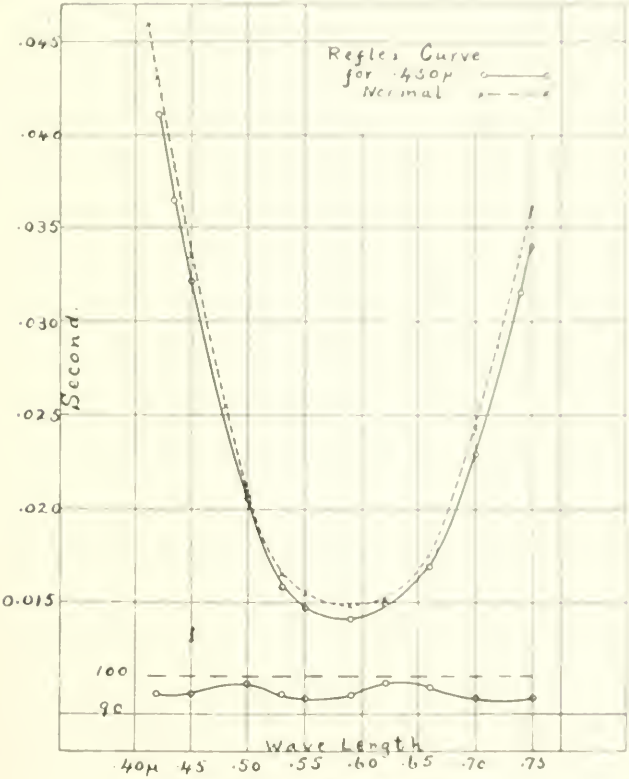

FIG. 9. Reflex curve for .450μ

TABLE 4. Curves for Wave Length .687μ

λ	Normal	Dim Light Adaptation	Darkness Adaptation	Daylight Adaptation
	Sec.	Sec.	Sec.	Sec.
660μ	0.0174	0.0171	0.0169	0.0166
620	.0152	.0149	.0147	.0145
590	.0148	.0145	.0142	.0137
550	.0155	.0151	.0147	.0141
530	.0165	.0161	.0155	.0151
500	.0209	.0204	.0200	.0198

These results show that all the depressions in the full curves previously discussed in this paper are really comparable with curve C.

TABLE 5. *Curves for Wave Length .450μ*

λ	Normal	Dim Light Adaptation	Daylight Adaptation
	Sec.	Sec.	Sec.
.590μ	0.0148	0.0145	0.0136
.550	.0155	.0152	.0142
.530	.0165	.0163	.0150

When darkness and dim light adaptation are both completely removed, the depressions should properly be enlarged to nearly double the depth in order to represent fully the reflex enhancement of the color sensations. It may also be inferred from Figs. 11 and 12, that enlargement of the depressions will also sharpen their three-fold division.

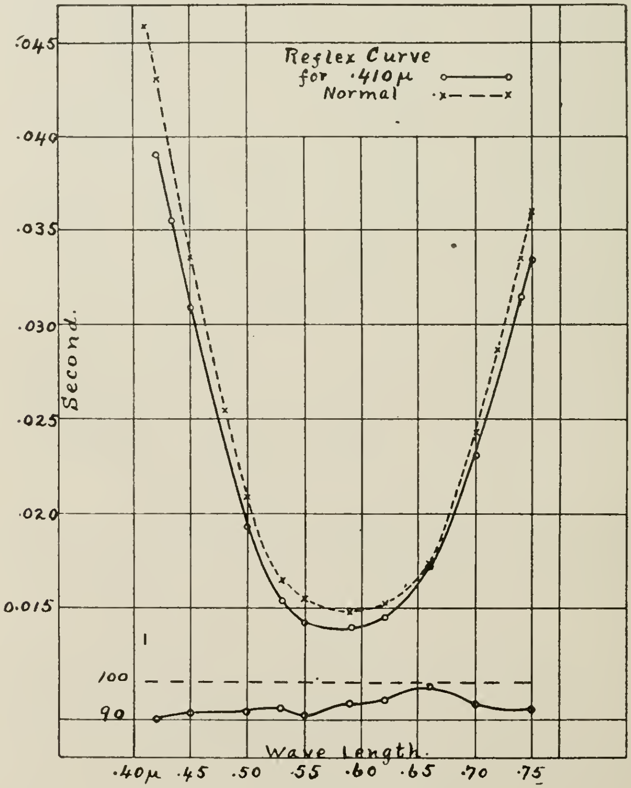

FIG. 10. *Reflex curve for .410μ.*

As so much time and labor had been expended in obtaining the curves shown in this paper, the writer did not repeat the measurements under the optimum condition of adaptation, contenting himself with the

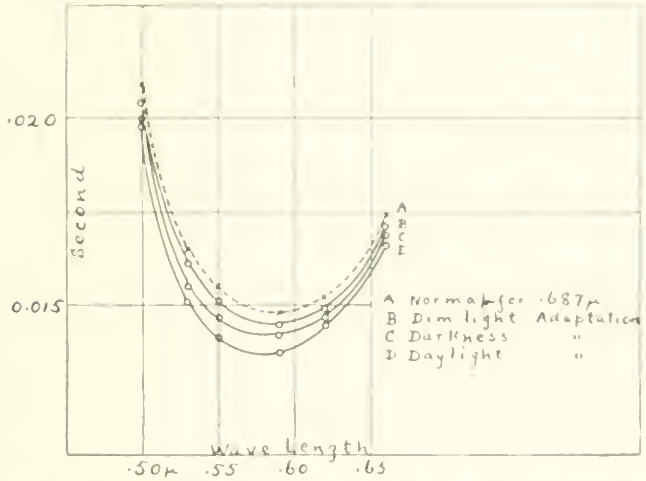

FIG. 11. *Partial reflex curves for wave length .687μ with different conditions of adaptation.*

double proof that they represent intermediate values of the reflexes, and that their real magnitudes are much larger than the curves indicate.

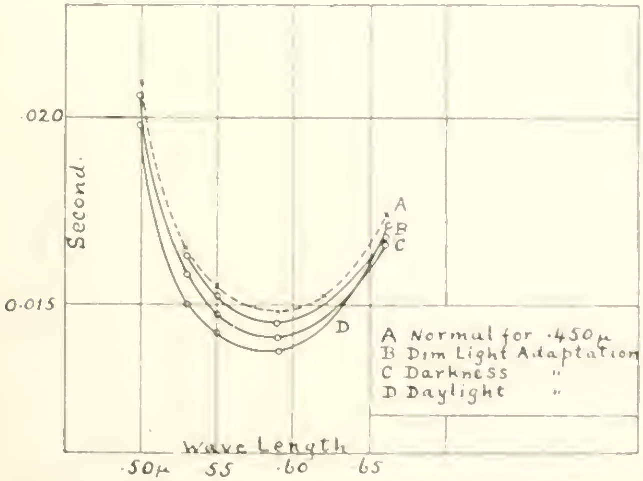

FIG. 12. *Partial reflex curves for wave length .450μ with different conditions of adaptation.*

The curve for the wave length .410μ, however, was obtained with the reflex area of the retina in sufficient daylight adaptation, and therefore probably represents the maximum reflex enhancement obtainable with this color.

The reflex effect of white light was also obtained by focussing a small but intense circular patch of white light from the arc upon the edge of a white porcelain plate. By fixating vision upon the edge of the plate a semi-circular patch like a half moon was formed on one side of the retina. The other adjoining side was illuminated by daylight reflected from the wall of the room behind the plate. The left eye was shielded so that it was only in daylight adaptation as before.

TABLE 6. *Luminosity Contrast*

λ	Normal	Darkness. Reflex	Darkness. Direct	White Light
	Sec.	Sec.	Sec.	Sec.
.750μ	0.0360	0.0348	0.0370	0.0344
.740	.0335	.0320	.0348	.0325
.720	.0287	———	———	———
.700	.0244	.0230	.0255	.0231
.680	———	———	———	———
.660	.0174	.0165	.0179	.0162
.640	———	———	———	———
.620	.0152	.0148	.0158	.0143
.590	.0148	.0142	.0151	.0136
.550	.0155	.0150	.0158	.0142
.530	.0165	.0160	.0169	.0153
.500	.0209	.0199	.0226	.0189
.480	.0255	———	.0285	———
.450	.0336	.0328	———	.0320
.433	———	———	.0432	———
.420	.0431	.0413	.0480	.0402
.410	0459	———	———	———

The measurements are given in Table 6. The curve, shown in Fig. 13, lies wholly below the normal, showing reflex enhancement of the brightness of the entire spectrum. The reduced curve at the bottom of the figure indicates a three-fold division corresponding to the color sensations.

It may be noted here that while observing the half disc of intense white light, there appeared on the other side of the retina, after about forty seconds, a dark olive green patch similar to the white in shape, but of about two-thirds the area. If the left eye was kept closed until the dark green patch was well developed, and then suddenly opened in daylight, the patch became for a few seconds bright green in color.

The effect of darkness adaptation of one area upon another was then studied. For this purpose a piece of black velvet was tied over one-half of the end of a paper mailing tube about fifteen inches long and two inches in diameter. This was directed against the light wall of the room. Vision was fixated on the edge of the velvet so that the side of the retina formerly fatigued was in darkness adaptation, and the other in daylight. It must not be overlooked that the inside of the long tube produced on the retina a dark area around the whole image of the black and white end of the tube.

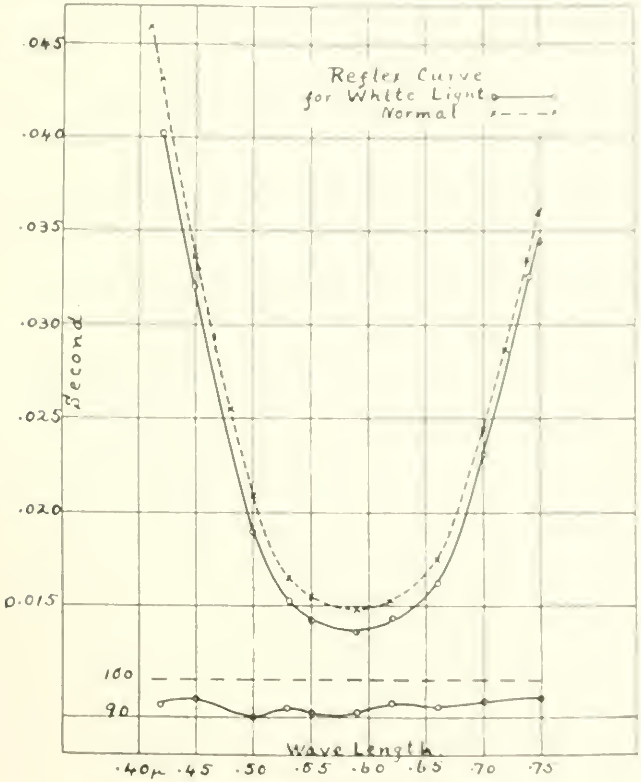

FIG. 13. *Reflex curve for white light*

The measurements obtained are given in Table 6, and are plotted as the lower curve, B, in Fig. 14. This curve shows that the whole spectrum was enhanced in brightness as the result of the transferred effect of darkness adaptation. By rotating the tube the conditions of adaptation of the retinal areas were reversed, and the direct effect of darkness was studied. These measurements showed that the brightness of the spectrum was diminished in all parts as indicated by the upper curve, A, in Fig. 14. Both reduced curves show recognition of the three sensations.

The enhancement of the brightness of a white surface may be readily seen by looking with one eye through a tube at a light surface, the other eye also being directed at the same. The exclusion of light from the peripheral retina of one eye by the long tube gives a circular band of darkness around the central disk of white on the retina. There is no illusion about the increased luminosity of the white to the eye at the tube, as the curve, B, shows the effect to be measureable and hence physiological and not psychological in its origin.

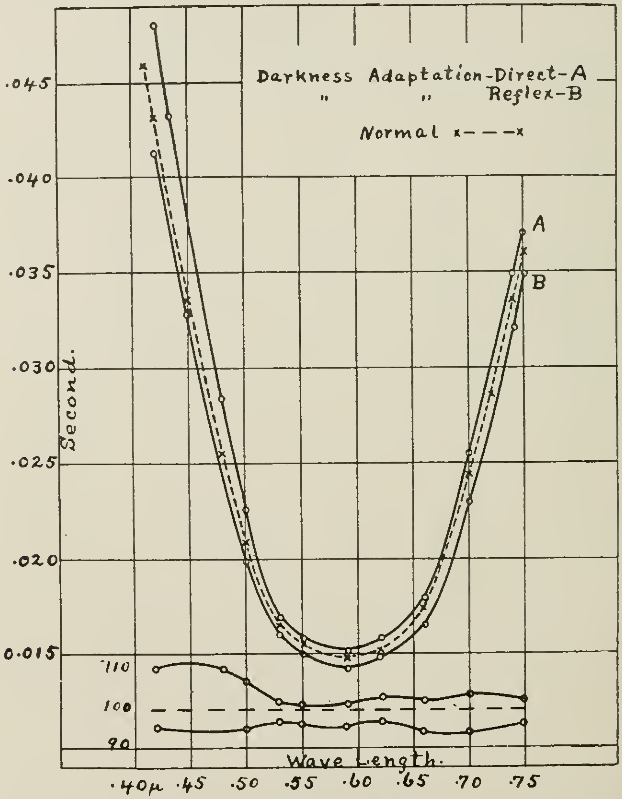

FIG. 14. *Curves obtained under different conditions of darkness adaptation.*

The inside of the eye pieces of observing instruments is usually painted dead black. This probably is primarily intended to absorb any stray or scattered light. From these experiments it is obvious that the surrounding darkness considerably enhances the brightness of whatever light or color is seen. It is equally obvious that in making exact and delicate measurements of the comparative brightness of light and colors, care must be exercised with regard to the conditions of adaptation of the unused eye and also of the different portions of the observing retina. All colors do not seem from Fig. 14 to be equally influenced by darkness enhancement, and quite appreciable errors may therefore be unwittingly introduced.

Though darkness has been regarded as a positive influence producing these effects, it is more probable that they are caused by preventing light from having the real positive influences.

From these experiments it may be concluded that light of every wave length falling upon an area of a retina enhances by reflex action the three fundamental sensations, red, green and violet in adjoining areas; also that the direct and reflex effects of the six equilibrium colors counterbalance each other so that no apparent fatigue or enhancement results. Never has the writer found in experiments upon his own eye evidence that fatigue, i. e., the direct action of light, was transferred from eye to eye, or from area to area on a single retina. The only transferable influences are effected through the agency of the visual sensory reflexes.

It is possible that direct effects may be transferred, and this may constitute a factor in abnormal vision. But in normal vision it seems possible to conclude that reflex effects of color are always transferred alone or in excess of the direct.

The curves described in this paper are identical with those obtained by reflex action from one eye to the other, which were described fully in the paper on reflex visual sensations, to which reference has been made.

II. THEORETICAL

Before proceeding to apply the experimental results to the elucidation of the phenomena of contrast or spatial induction, we may with advantage summarize briefly our present knowledge of the two-fold action of light upon the retina.

The first part consists of the direct action which when continued produces fatigue, and in consequence, diminishes luminosity by enfeebling the response of the receptor elements of the retina. The direct action of each color was considered by Helmholtz always to cause stimulation of all three sensations. From this doctrine Abney[12] dissented in part; for he considered that "the red stimulates only the red sensation in one part of the spectrum, whilst the violet stimulates both the red and the blue, and not the green sensations. A green color not only stimulates the green sensation, but it stimulates the red and blue sensations as well, as is shown in Helmholtz's diagram."

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[12] Researches in Colour Vision, p. 231.

Experimental evidence already obtained in the writer's laboratory through the study of abnormal vision, the results of which will be published in due course, are in agreement with the assumption of Helmholtz. The writer therefore feels justified in concluding that the direct action of light stimulates all three sensations, but that the predominant effect extends to the one sensation chiefly involved if the color is simple, i.e., red, green, or violet, and to the two sensations chiefly involved if the compound colors, orange, yellow, and blue are employed.

The reflex effect, the second part of the dual visual process, always produces enhancement of the three sensations, but the predominant effect is upon the sensations complementary to the active color. The characteristic reflex influences are transferred from eye to eye, and from one retinal area to the parts adjoining. In brief the predominant direct and reflex effects of an active color are complementary to each other.

We may now consider how two contiguous patches of color, e.g., yellow and green, affect each other when viewed by a single retina, vision being fixated on a point in the junction of the patches. The reflex effect of yellow is transferred to the area occupied by the green, resulting in enhancement of all three sensations, red, green, and violet, though the predominant enhancement covers the complementary of yellow. The green light directly affects all sensations, but predominantly the green. Since the complementary of yellow is now enhanced, the green stimulates that more than is normally the case, with the result that consciousness now perceives green mixed with the complementary of yellow. Similarly, on the adjoining area yellow is perceived mingled with the complementary of green. Thus yellow and green are both perceived mingled with the complementary of each other. But it must not be forgotten that since all three sensations are enhanced in sensitiveness in each case, the complementary modification of colors is only a predominant effect, and probably can never absolutely be realized.

Since the complementary of green is purple, a mixture of red and violet sensations in which red is predominant, it follows that the contrast modification of yellow is more in the direction of red than of violet; that is, yellow when contrasted with green appears to be moved away from its green competitor in the spectrum towards the red. Similarly the green will be mixed with the complementary of yellow, which is ultramarine-blue, and therefore appears to be moved away from the yellow towards the violet.

These conclusions are in harmony with the statements of Parsons,[13] who says: "The most important element in colour-contrast from our present point of view is the opponent or complementary effect . . . Under ordinary circumstances the induced color is not the precise complementary of the inducing . . . ." Likewise Rood[14] states that "when two colored surfaces are placed in contiguity, each is changed as though it had been mixed to some extent with the complementary color of the other"; and also[15] that the effect produced by contrast is apparently to move the spectral colors both farther apart.

From the point of view of this paper, contrast is not a relative effect, as it is frequently considered to be,[16] but is absolute in the sense that the modification of color is as physiologically real as are the original colors.

If the two contrasting colors are normally complementary, their mutual reflex enhancing effects of necessity will accord predominantly with the active colors themselves. There will therefore be a marked increase in the brightness and saturation of the colors. There ought to be, however, some alteration, though possibly but slight, in hue.

Since the predominant reflex influence enhances the complementary of a color, it also follows that similar colors when contrasted will lose in brightness, for the amount of enhancement each receives from the other is insufficient to compensate the loss in brightness due to fatigue. The reflex stimulation of all three sensations results in the production of white which therefore will lessen the saturation of the colors. Some modification of the hue, however, again should result.

These conclusions also agree with those of Rood.[17]

The further remark of Rood[18] that the changes in hue and saturation of intense, pure, and brilliant colors are particularly conspicuous after somewhat prolonged observation is also in harmony with the experimental results described in the first part of this paper, for the marked reflex enhancement of portions of the spectrum shown by the depressions of the curves, were obtained after exposing the eye to intense colors for about two minutes before each measurement was made. No doubt the reflex action follows very rapidly after the direct exciting color, but it grows in magnitude with time until the maximum or saturation point is reached.

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[13] Colour Vision, p. 128.

[14] Modern Chromatics, p. 244.

[15] Ibid., p. 246.

[16] See e.g. Peddie, Colour Vision, p. 21.

[17] Modern Chromatics, p. 247.

[18] Ibid., p. 252.

Though the writer has no experimental evidence to adduce regarding the character of the reflex effects of weak colors, yet it can scarcely be doubted that reflex effects are excited by them proportionately with intense colors. Investigation perhaps would show that the reflex action is even disproportionately large; and there can scarcely be any doubt that the changes due to reflex influence would be perceptible in a far shorter time.

When pale colors are contrasted it is well known that most striking modifications occur at the first glance. But in these cases the results of the reflex enhancement of the complementary sensations must be apparent the moment they are aroused. The very delicacy of the active colors renders the least modification of tint noticeable.

There seems therefore to be no essential difference between the contrast effects of pale colors and those of intense colors, and an explanation satisfactory for one may be considered quite applicable to the other. Simultaneous contrast is closely allied with successive contrast; the difference from the present standpoint is largely, perhaps altogether, the degree to which the several reflexes are permitted to develop.

There is already some evidence that the reflexes do not develop in the same time. Probably, too, the rates of excitation and development are dependent on wave length and luminosity. These matters, it is hoped, will be discussed in a later communication. It seems quite probable, however, that contrast effects with intermittent illumination will generally not be quite the same as with steady observation.

The explanation of contrast advanced by Helmholtz and adopted by Rood is that it is due to errors of judgment. Two experiments described by the latter[19] to enforce this explanation may with advantage be considered here.

"We carry in ourselves no standard by which we can measure the saturation of color or its exact place in the chromatic scale; hence, if we have no undoubted *external* standard at hand with which to compare our colors, we are easily deceived. A slip of paper of a pale but very decided blue-green hue was placed on a sheet of paper of the same general tint, but somewhat darker and more intense or saturated in hue. The small slip now appeared grey, and by no effort of the reason or imagination could it be made to look otherwise. In this experiment no undoubted pure grey was present in the field of view for comparison, and in point of fact the small slip did actually approach a pure grey in hue more nearly than the large sheet; hence the eye instantly accepted it for pure grey. The matter did not, however, stop here. A slip of pure grey paper was now brought into the same green field, but, instead of serving as a standard to correct the illusion, it assumed at once the appearance of a *reddish* grey. The pure grey really did approach reddish-grey more than the green field surrounding it, and hence was accepted for this tint. The same pale blue-green slip, when placed on a pale-reddish ground, assumed a stronger blue-green hue than when on a white ground. In the first of these experiments we have an illustration of harmful and in the second of helpful simultaneous contrast. The result in both cases coincided with that which successive contrast would have produced under similar circumstances."

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[19] Modern Chromatics, p. 253.

The principle of reflex sensations provides a physiological explanation of a radically different character.

The intense blue-green of the large sheet enhances reflexly the three color sensations in the retinal area covered by the pale color, but predominantly the sensations complementary to the exciting color. The pale blue-green stimulates not only its own proper sensations but also the enhanced complementary to an extent much greater than normally is the case. The pale blue-green and its complementary therefore unite to give the observed grey appearance.

In the second experiment, the light from the grey paper in its turn fell upon the same enhanced sensations, stimulating especially the part complementary to the intense blue-green. As the grey paper has no color of its own to unite with this complementary, the latter is seen alone. Hence the grey paper appears reddish-grey.

In the third experiment, the reddish color of the ground enhanced its complementary sensation which is blue-green. Hence the latter does not modify the pale blue-green color, but intensifies its appearance.

In all three cases the changes in color of the pale blue-green and other papers are as much physiological realities as are the original colors. Instead of the judgment being 'deceived,' it is, on the contrary, extremely truthful and accurate in estimating the collective result of the composite physiological processes involved in the contrast modification of color. Contrast is due to the remarkable accuracy of the judgment instead of its deception.

As a second example of contrast the famous experiment on coloured shadows may be considered. This is described in great detail by Rood.[20] Two shadows of an obstacle are simultaneously cast on a white surface by white daylight and an orange-yellow candle flame. All parts of the surface are therefore illuminated by the yellowish candle light, except the shadow cast by it. This will be illuminated only by daylight, but by contrast with the yellowish surface will appear decidedly blue. "For the production of the most powerful effect, it is desirable that the shadows should have the same depth, which can be effected by regulating the size of the aperture admitting daylight. Now, although the shadow cast by the candle is actually pure white, yet, by contrast with the surrounding orange-yellow ground, it is made to appear decidedly blue. So strong is the illusion that, even after the causes which gave rise to it have disappeared, it still persists, as can be shown by the following experiment of Helmholtz: While the colored shadows are falling on the screen, they are to be viewed through a blackened tube of cardboard, held in such a way that the observer has both the shadows in his field of view. After the blue shadow has developed itself in full intensity, the tube is to be moved so that the blue shadow may fill the whole field. The tube being held steadily in the new position, the shadow will still continue to appear blue instead of white, even although the exciting cause, viz., the orange-yellow candle-light, is no longer acting on the eye. The candle may be blown out, but the surface will still appear blue as long as the eye is at the tube. On removing the tube, the illusion instantly vanishes, and it is perceived that the colour of the surface is identical with that of the rest of the screen, which is at once recognized as white. In a case like this the fatigue of the retinal elements can play no part, as the illusion persists during a far longer period of time than is necessary for their complete rest; we must hence attribute the result to a deception of the judgment."

By applying the principle of the visual sensory reflex, the phenomena may be given a simple physiological explanation. The orange-yellow light surrounds the small retinal area upon which falls the white light coming from the shadow cast by the candle. The reflex action of the yellowish light upon the protected retinal area causes enhancement of all three fundamental sensations, but predominantly the portion of the sensations complementary to yellow. The white light in consequence stimulates this part to a much greater extent than the remainder, and the light in consequence is perceived as blue.

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[20] Modern Chromatics, p. 254.

The crucial experiment devised by Helmholtz to prove his theory of illusions is easily understood. Though it is carefully specified that the observation must be made through a blackened tube, the effect of the tube on the retina is ignored with equal care by both Helmholtz and Rood. A reference to the lower curve B in Fig. 14, shows, as explained above, that darkness on one area of the retina results in a physiological enhancement of light and color on the adjoining areas. Now the blackened tube causes a dark retinal area around the image of the colored shadows, which greatly enhances the yellow candle light and, by its increased reflex action, the complementary blue also. After viewing this for some time for the purpose, as Rood says, of allowing the blue shadow to develop itself in full intensity, or, as the writer would state it, of permitting the reflex action to cause its maximum enhancement, the tube is moved so that the blue shadow only is seen without the yellow surrounding regions. The blue color is then found to persist for a considerable time.

But why should it not persist? It takes several minutes for the violet reflex enhancement to develop to its full intensity; it is not surprising therefore that it should also persist for a considerable time. Burch[21] found that after-image effects last for as much as two hours. There is quite sufficient reason therefore for the persistence of the blue shadow, even when the candle flame was blown out.

When the blackened tube is removed from the eye, the powerful enhancement due to darkness also disappears, and the white light from the screen by its direct and reflex actions quickly equalizes the stimulation of all the sensations, and the blue color disappears.

A similar explanation will apply to all other complementary shadows. But while no measurements have yet been made on the rate of growth or of decay of the reflex enhancement of colors, there is reason to anticipate that colored shadows will persist for continually shorter intervals of time, as the color approaches the red end of the spectrum.

An experiment quite analogous to that just discussed was devised by Hering to prove the psychological principle that under certain conditions "the ultimate perceptions depend not upon differences of physical light intensity, but upon other impressions which simultaneously enter into consciousness and modify judgment."

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[21] Parsons, Colour Vision, p. 112.

The experiment is thus described by Parsons from whose work on Colour Vision (p. 23) these quotations are taken: "In a room lighted by a window on one side, the opposite wall being white, standing with the back to the window and holding up a grey sheet of paper, the paper looks grey and the wall white. The wall however reflects only a portion of the light into the eye and 'is' therefore grey. By looking through a tube it is possible to select a grey paper which exactly matches the greyness of the wall; yet directly the tube is removed the wall at once appears white, whilst the paper still remains grey. If, however, the edge of the paper is fixed with one eye only, the wall appears to be on the same plane and of the same tint as the paper."

The experimental results previously discussed on the enhancing effect of darkness on adjoining areas of the retina show that papers of varying degrees of greyness, or brightness, when viewed with one eye through a dark tube, the other eye meanwhile being directed at the white wall, will all appear much brighter than without the tube. Finally a paper is selected whose enhanced physiological brightness is the same as that of the wall. When the tube is removed the enhanced part of the brightness also disappears and the paper is seen by the unaided eyes darker than the wall, as of course it should be.

In the second part of the experiment if one eye is closed or blindfolded while the other is used to fixate the edge of the paper, the result, as shown by the experiments of the writer, is that both wall and paper must appear darker. On one side of the median line of the active retina is the light from the darker grey paper, and on the other side adjoining is the light from the brighter wall. These two influence each other physiologically by reflex action; the bright wall enhances greatly the brightness of the darker grey, and the dark grey only slightly enhances the brightness of the wall, or if the grey be quite dark, it will diminish instead of enhancing the brightness of the wall. The enhancement of the grey paper with the dark tube in the first part of the experiment exactly balances, as the result shows, the double change of brightness in the second part.

Parsons further states that "Hering points out that these facts have nothing to do with simultaneous contrast as has sometimes been thought. They are indeed examples of the association of ideas or sympsychosis." But from the experimental evidence adduced in this paper, the effect can be explained on physiological principles without reference to psychology.

The usual effect of simultaneous contrast is to emphasize and increase differences between contiguous luminous and color fields. Since in the Hering experiment the difference in luminosity is eliminated the effect may be termed reversed simultaneous contrast or induction.

In several places in this paper darkness is spoken of for convenience as though it produced positive reflex effects. This of course is impossible. The apparent enhancing effect obtained by looking through a dark tube may be accounted for without difficulty. It is known from experiments described in the paper on reflex visual sensations previously referred to, and also from Figs. 11 and 12 in this communication, that dim white light exercises the greatest reflex effect in diminishing brightness. If the eye is directed at a white surface the light falling on the peripheral parts of the retina makes a much more feeble impression than that on the central region. Consequently the dim light on the periphery by its reflex action diminishes or partially inhibits the luminous response of the central part of the retina thus rendering the light falling upon it physiologically less bright than it properly should be. If complete darkness replaces the dim light, the inhibiting effect is removed and the brightness of the central light increases to what it should be, thus causing the apparent enhancement.

In explanation of luminosity contrast between black and white surfaces, the reflex curves in Figs. 13 and 14 show that darkness enhances the physiological brightness of the adjoining light surface, which in turn also causes the black surface to appear lighter. This is in conformity with what is commonly observed when a black square is placed on a white surface.

With gray contrasting surfaces of varying degrees of lightness there will probably be variations in their aspect due to the fact, as shown previously in this paper, that dim or weak white light has effects, both direct and reflex, entirely peculiar to itself. These effects, while definitely shown, are not yet fully understood, and the writer hopes to undertake their investigation as opportunity offers.

There is also an important series of contrast effects obtained when positive colors are placed on white, black, or gray surfaces. Since the direct stimulation of each retinal area affects reflexly the contiguous areas, there will be a reciprocal modification of the appearance of the contrasting surfaces. In general the fields surrounding colors will be tinged with the complementary of the active colored light.

But since both white light and darkness enhance by reflex influence all three sensations, but in unequal amounts, the modification of the contrasting color will vary with its hue and saturation. In general there will be changes both in hue and brightness.

It is impossible to consider in detail how each of the innumerable contrast effects observed are to be explained. With the principle outlined above clearly in mind, the large numbers of contrast effects described by such authors as Rood[22] and Edridge-Green[23] may be readily accounted for.

In his recent work on "Colour Vision," Peddie[24] introduces the term "defatigue" which he thus defines: "Fatigue is evidently an aspect of light adaptation; and its converse the Recovery from Fatigue, or Defatigue, is an aspect of dark adaptation. It is the time change of fatigue or of defatigue which constitutes the process of adaptation."

In many places in his work Peddie makes great use of defatigue. One quotation, p. 172, however, will illustrate his idea of this phenomenon. "In a non-uniformly illuminated white field, defatigue of the darker parts may brighten these in spite of their own illumination which produces fatigue, and fatigue of the bright parts by their own illumination may be more effective than their defatigue by the adjacent less bright illumination. In this case the tendency would be for the illumination to become gradually more uniform in aspect, and this effect is well known. If one directs the gaze fixedly towards a point in a shaded part of a white ceiling, the shaded parts will seem to brighten appreciably by slow degrees, the contrast becomes less between the shaded part and its brighter surroundings, and at last all difference disappears and only a uniform field is seen. But the illusion is destroyed at once by even a slight motion of the line of vision, as it should be."

It is quite obvious from the experimental results discussed in the first section of this paper, that the enhancement of the visual sensations in one retinal area by reflex action from an adjoining area is identical with what Peddie terms defatigue. The process of enhancement is so fundamentally different from the direct action of light, that the use of the word, defatigue, to describe it, will obscure the ascertained cause, and in consequence will be very misleading. In the opinion of the writer the word should not be employed in describing the phenomena of enhanced sensations.

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[22] Modern Chromatics, Chapter XV.

[23] Physiology of Vision, Chapter XXVI.

[24] p. 148.

Since the six equilibrium colors, .660μ, .572μ, .520μ, .505μ, .480μ and .425μ, are incapable of producing fatigue or enhancement, or at most very feeble effects, it would appear to follow that they will not modify each other by contrast, either in hue or brightness. White and black surfaces also should not be modified in appearance by contrast with equilibrium colors, though these colors themselves should be modified, either in hue or brightness or in both, by the white light or darkness.

If an equilibrium color is contrasted with a non-equilibrium color, the former should be modified by the reflex influence of the latter, but the latter should experience no modification either of hue or luminosity due to the former.

If such observations were to be made as suggested, care would have to be taken with regard to the presence of contiguous dark or very bright areas which, as the reflex curves show, have their own effects on the physiological brightness of colors.

Should it be found that slight changes in the wave lengths of contrasting colors abolish simultaneous contrast effects, the usual explanations of the phenomena as "due to unconscious eye-movements, to incipient retinal fatigue, to fluctuations or error of judgment," would at once be eliminated, and the reflex principle confirmed.

The writer has not tested these deductions from the principle, and hence cannot say whether experiment will verify them or not.

Since it is probable that the three reflexes develop in unequal times, it would appear to follow that the contrast effects produced by intermittent vision will be different from those obtained with steady illumination. With intermittent illumination the equilibrium colors may also produce contrast effects.

In the former paper on reflex visual sensations,[25] it was briefly pointed out that binocular contrast was explained by the reflex effects of color being transferred from one eye to the other. The explanation is identical with that for monocular contrast herein described. For the persistency curves obtained by reflex action from one eye to the other are identical with those obtained from one retinal area to another, with the partial exception of the influence of darkness.

It has been found by Mayer[26] that contrast effects were perceptible when the illumination of the colors was obtained from an electric spark, the duration of which was of the order of one ten-millionth of a second. But in such experiments care must be taken to distinguish between the time of the physical stimulus and the duration of the physiological effects of momentary stimulation. With this distinction in mind, these observations are not at variance with the reflex principle. For it has been found in the study of reflex action generally that[27] "the discharge from a reflex arc does not, as a rule, cease when the stimulus ceases, often lasting for five seconds or more. The duration is proportional to the intensity of the stimulus. With a weak stimulus, the response may not appear at all until after the actual period of stimulation has passed."

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[25] J. O. S. A. & R. S. I., p. 583, 1923.

[26] Am. Jour. Sci., July, 1893. Also Luckiesh, Color and Its Applications, p. 178.

It has been widely recognized that the phenomena of simultaneous and also of successive contrast involve processes occurring in the visual centres, and on that account they have been regarded as psychological in their nature. The reflex principle seems happily to combine the physiological and the apparently psychological factors. For the direct stimulation of the afferent nerve fibres must first be conveyed to the visual centres, and there excite activity in the efferent nerves by means of which contrast effects, both simultaneous and successive, are produced. The psychological factors are indeed ruled out, but the physiological reflex still requires the visual centres in the brain for its operation. The explanation of contrast is thus pushed back one step further; but its ultimate elucidation must rest until some future investigator discovers how the physiological process is transmuted into the consciousness of color.

This research is a part of the general investigation of Color Vision now in progress with the financial assistance of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa; to which body the writer desires to express his thanks.

DEPARTMENT OF PHYSICS,
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JULY 10TH, 1923.

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[27] Principles of General Physiology. Bayliss, p. 489, 3rd Ed., 1920.

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ON REFLEX VISUAL SENSATIONS

BY

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ON REFLEX VISUAL SENSATIONS*

By Frank Allen

Synopsis

Section I of this communication contains a very brief summary of previous work of the author on the application of the method of the critical frequency of flicker to the determination of the primary color sensations. Attention is specially directed to the fact that former investigations were conducted in a dark room, so that while the right eye was stimulated by light from the spectrum, the left eye was in darkness adaptation. It was generally believed that darkness adaptation of one eye had no influence upon the other.

Section II contains descriptions of experiments made in a room illuminated by ordinary daylight. The right eye was in daylight adaptation while the left eye was fatigued with spectral lights. All measurements of the critical frequency of flicker were made with the right eye. It was found that the stimulus applied to the left eye was transferred to the right eye by some reflex process resulting in an enhancement of the brightness of three colors, which were always red, green, and violet. Six colors were found, viz., $.660\mu$, $.570\mu$, $.520\mu$, $.505\mu$, $.480\mu$ and $.425\mu$, which produced no effect. The reflex and normal curves always coincided in two places which averaged about $.653\mu$ and $.50\mu$. The magnitude of the reflex effect is greatest for the violet color, and seems to vary as some inverse function of the wave length.

Section III contains the description of experiments performed when the right eye was fatigued and the left was always in daylight adaptation.

It was found that fatigue produced both a direct and a reflex effect. The red, green, and violet colors showed one elevation of the fatigue curve above the normal in the part corresponding to the color used, and two reflex depressions in parts corresponding to the remaining primary colors. The compound colors, yellow and blue, produced two elevations in the parts of the curves corresponding to the color sensations of which they are compounded, and one reflex depression in the part corresponding to the remaining color. The number of elevations or depressions in each curve was always three, corresponding to red, green and violet.

The six colors mentioned above produced no effect, and are termed equilibrium colors.

The effect of darkness adaptation of one eye upon the other is shown to cause a diminution of brightness of the whole spectrum. This is applied to explain Fechner's paradox.

Section IV contains theoretical applications to explain the cause of the whiteness underlying all color sensations, successive contrast, binocular contrast, non-saturation of colors,

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saturation of colors in after images, the duplicity theory of von Kries, complementary colors, and to theories of color vision.

Section V contains anatomical and physiological considerations which render it probable that the effects discovered are due to a new kind of physiological reflex which is termed a sensory reflex.

I.

In former communications[1] to the Physical Review and the Philosophical Magazine, studies were made of the effect of fatiguing the eye with various spectral hues on the color sensations. The method used was to determine the persistence of vision, or, as it is less euphoniously but more exactly termed, the critical frequency of flicker, of successive colors of the spectrum, when the eye was first in its normal and then in a fatigued condition. The two sets of measurements were expressed as persistency curves, of which many new examples are shown in this communication. The coincidences and divergences of the curves enabled conclusions to be drawn regarding the number of the fundamental color sensations, and the limits of the hues of the spectrum by which they are excited. It was found that the divergences of the curves, in the form of elevations above the normal, occurred only in three portions which correspond to the red, green and violet regions of the spectrum. Each of these three colors caused one elevation in the part of the spectrum corresponding to itself; but the remaining colors each caused two elevations which were pairs of those obtained with simple colors. It was found that when the retina was fatigued with the four colors, $.660\mu$, $.570\mu$, $.470\mu$, and $.420\mu$, the normal and fatigue curves coincided, and these transition points were believed to mark the boundaries between the simple and compound colors.

From the point of view of the present investigation, it is most important to bear in mind the conditions under which the former curves were obtained. The Nichols Apparatus,[2] as it may be termed, consisting of a constant acetylene flame, a rotating sectored disk, and a spectrometer, with suitable electric recording devices for measuring the speed of the disk, was set up in a dark room. The normal curve was made with the right eye when both eyes were in daylight adaptation. The fatigue curves were obtained while the observer stayed in the dark room continuously for from two to three hours. Thus the left eye of the observer was in continuous darkness adaptation while the right eye was being fatigued. When these curves were being obtained, it was supposed that the simplest condition of the eye prevailed. It was not suspected in the least that darkness adaptation of one eye affected the other. It must not, however, be inferred from the new curves about to be considered that the old are wrong but only that they represent the combined effect of fatigue of one eye and the transferred effect of darkness adaptation of the other.

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[1] Phil. Mag. *38*, p. 56; 1919.
Phys. Rev. *11*, p. 257; 1900.

[2] E. L. Nichols, Am. Jour. Sci. *28*; 1884. Also, Allen, Phil. Mag. loc. cit. and Phys. Rev. loc. cit.

II. Reflex Curves

The experiments now to be described differ from those just referred to, in two important particulars. First, the traditional dark-room, inherited from Newton, was abandoned, and the apparatus transferred to a room well illuminated by ordinary daylight. Second, the left eye only was maintained in a state of fatigue and the critical time of flicker was measured by the right eye which was constantly in daylight adaptation. The instruments were properly screened from all extraneous light, and a shield, fitted to the eye, was attached to the eyepiece of the observing spectrometer, which enabled all measurements to be made under exactly the same conditions. So constant were the acetylene flame, which supplied the observing spectrum, the position and adjustments of all apparatus, and notably the retina in its ordinary condition, that the normal curve remained the same for the five months during which these researches were in progress. The use of a lighted room also enabled the work to be done under far more agreeable physical conditions, and the curves are much more fully and exactly determined than formerly.

The spectrum used for fatigue was obtained from an arc light with a two-prism Browning spectrometer, and was so intense that the colors in the middle approached whiteness in appearance. A narrow but quite long rectangular portion was isolated with a shutter eyepiece and the wave lengths mentioned in this paper are for the centre of this band. The measurements were made upon a much shorter and slightly narrower band in the eyepiece of a four-prism Hilger spectrometer. The centre of the retina in each eye alone was used.

In making observations, an invariable procedure was followed. First, all instruments were placed in adjustment and in readiness for recording the speed of the disk; second, the eye was exposed to the fatiguing light for from two to three minutes; and, finally, the speed of the disk was adjusted for the critical frequency of flicker and recorded. Only one fatiguing color was used on any day, except for some partial curves. The time required to obtain all the measurements for a curve was about three hours, sometimes employed continuously, sometimes divided into two portions. At least two independent chronographic records, each giving several readings, were made for each point of a curve. The values used in plotting were usually means of six, except for the ends of the spectrum. The character of the curves was determined by the first set of readings; but for the sake of smoothness, which is the obvious characteristic of the spectrum, additional readings were taken for all doubtful or apparently misplaced points. As all conditions were constant there was no limit to the number of determinations which might be made. In each figure, two curves are plotted, one, the normal or reference curve, which throughout is uniformly shown as a dashed line, the second, that which is obtained with the eye in some abnormal condition. With no exception, all curves described in this paper were made with the right eye of the author.

The two curves are plotted together to the same scale, and by their coincidences and divergences show the effect of the color stimulus under study, as far as it can be shown by this method.

At the bottom of each figure the same curves are reproduced in another form by giving the normal curve an arbitrary value of 100 in all parts, and reducing the other curve in the same proportion. This enables the position and extent of the divergences to be readily seen. The position of the fatiguing color is indicated by a short, vertical line.

The retina is not very sensitive to small changes in the brightness of colors when directly observed. But a variation in brightness that changes the mean value of the critical frequency of flicker by 0.0002 second can quite confidently be measured for the brighter colors in the middle of the spectrum. It is known[3] "that the point of fusion of intermittent stimuli, so as to produce a continuous sensation, depends, not on the physical intensities of the stimuli, but on their physiological intensities, as determined by the condition and nature of the stimulated retina." It has also been proved by Ferry[4] and by T. C. Porter[5] "that the duration of the undiminished sensation produced by different spectral hues depends solely on the luminosity of the colors and not on their wave frequency."[6] We are justified therefore in inter-

[3] Quoted from Rivers in Parsons, "Colour Vision," p. 95.

[4] Am. Jour. Sci. *3*, p. 44; 1892.

[5] Proc. Roy. Soc. *63;* 1898.

[6] Parsons, loc. cit. p. 96.

preting an elevation of the abnormal curve above the normal as a decrease in the physiological brightness of the corresponding part of the spectrum; a depression below the normal as an increase in the brightness; and coincidence of them as indicating no change whatever.

At the outset it was a matter of conjecture what changes would occur to one eye when the other was fatigued. The character of the curves could not in the least be anticipated. That certain color and light effects are transferred from one eye to the other is well known. An observation of Burch's[7] which the author happened upon during the progress of the investigation, is connected with this subject and has possibly some practical applications in connection with the use of the microscope and telescope. Burch observed that when one eye is illuminated by bright white light, the scintillations in a spinthariscope are rendered much more brilliant to the other eye which has meanwhile been kept in darkness.

The curves were not obtained in the systematic order in which they are here presented, and the precise colors used were selected for reasons which presented themselves as the work progressed. The data for all the curves discussed in this section are given together in Table 1.

TABLE 1. *Reflex Curves*

λ	Normal	740μ	690μ	687μ	677μ	660μ	625μ	577μ	570μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
750μ	0.0360	0.0351	0.0339	0.0337	0.0339	0.0366	0.0332	0.0324	0.0355
740	.0335	.0328	.0318	.0316	....	.0329	.0306	....	.0331
720	.0287	.0283	.0274	.0272	.0278		.0266	.0265	.0280
710	....	....	....	....				.0247	
700	.0244	.0237	.0236	.0238	.0236	.0243	.0230	.0223	.0245
680	....	....	....	.0202	.0199	....	.0196	.0186	.0201
660	.0174	.0172	.0172	.0172		.0173	.0171	.0159	.0174
640	....	.0158	....	.0151	.0156	....	.0154	.0146	.0159
620	.0152	.0148	.0147	.0141	.0148	.0154	.0146	.0139	.0151
590	.0148	.0143	.0139	.0135	.0140	.0147	.0142	.0136	.0145
550	.0155	.0148	.0146	.0142	.0148	.0152	.0148	.0145	.0153
530	.0165	.0159	.0157	.0154	.0161	.0164	.0156	.0155	.0164
520	....		.0165	....	....	....	....		
506			....	.0196	....		.0190	.0192	
500	.0209	.0201	.0204	....	.0212	.0207	.0208		.0206
480	.0255	....	.0249	.0255	.0247	.0250	.0252	.0253	.0251
450	.0336	.0325	.0328	.0328	.0321	.0341	.0321	.0326	.0333
433	....	....	....	.0369	.0363	....	....		
420	.0431	.0422	.0408	.0407	.0409	.0431	.0406	.0406	
410	.0459	.0455	.0430	.0433	.0433	.0461	.0435	.0436	.0451

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[7] Burch: "Physiological Optics," p. 91.

TABLE 1. *Reflex Curves (continued)*

λ	.550μ	.530μ	.520μ	.515μ	.505μ	.495μ	.480μ	.460μ	.450μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.750μ	0.0322	0.0326	0.0353	0.0353	0.0358	0.0346	0.0354	0.0336	C.0331
.740	.0308	.0306	.0337	.0334	.0333	.0324	.0332	.0316	.0307
.720	.0273	.0266	.0284	.0284	.0282	.0271	.0281	.0273	.0270
.700	.0234	.0230	.0245	.0241	.0241	.0233	.0242	.0235	.0233
.680	.0200	.0197	....	....	....	....	....	.0198	.0197
.660	.0172	.0171	.0170	.0176	.0177	.0173	.0173	.0172	.0173
.640	.0158	.0161	.0158	.0161	.0161	.0159	.0160	.0160	.0159
.620	.0151	.0146	.0154	.0153	.0153	.0148	.0151	.0152	.0149
.590	.0144	.0140	.0147	.0144	.0148	.0141	.0148	.0144	.0141
.550	.0148	.0144	.0153	.0147	.0153	.0146	.0153	.0148	.0148
.530	.0159	.0155	.0161	.0156	.0165	.0157	.0163	.0157	.0157
.500	.0205	.0201	.0207	.0202	.0213	.0204	.0206	.0204	.0205
.480	.0243	.0237	.0254	.0238	.0262	.0249	.0256	.0250	.0247
.467	....	....	.0294	.0268	.0292	.0278	.0284	....	.0279
.450	.0318	.0318	.0333	.0318	.0334	.0326	.0342	.0322	.0313
.433	....	....	.0391	.0368	.0387	....	.0381	.0369	.0354
.420	.0390	.0399	.0430	.0407	.0425	.0416	.0432	.0414	.0397
.410	.0421	.0418	.0450	.0436	.0463	.0454	.0455	.0437	.0425

λ	.425μ	.420μ	.410μ	White	Darkness				
	Sec.	Sec.	Sec.	Sec.	Sec.				
.750μ	0.0356	0.0348	0.0341	0.0337	0.0390	....	....	....	....
.740	.0333	.0325	.0319	.0314	.0353	....	....	....	....
.730	....	....	.0296	....	....	....	....	....	....
.720	.0284	.0278	.0271	.0267	.0302	....	....	....	....
.710	....	....	.0254	....	....	....	....	....	....
.700	.0246	.0240	.0234	.0232	.0260	....	....	....	....
.680	.0196	.0203	.0200	....	....	....	....	....	....
.660	.0173	.0173	.0173	.0164	.0190	....	....	....	....
.640	.0160	.0161	.0153	.0153	.0173	....	....	....	....
.620	.0153	.0151	.0140	.0145	.0161	....	....	....	....
.590	.0148	.0144	.0134	.0138	.0156	....	....	....	....
.550	.0152	.0151	.0140	.0143	.0163	....	....	....	....
.530	.0164	.0160	.0153	.0155	.0178	....	....	....	....
.500	.0205	.0204	.0193	.0194	.0222	....	....	....	....
.480	.0248	.0260	.0234	.0237	.0271	....	....	....	....
.467	.0282	.0288	.0259	....	....	....	....	....	....
.450	.0331	.0333	.0306	.0319	.0363	....	....	....	....
.433	.0392	....	.0358	.0360	.0433	....	....	....	....
.420	.0430	.0422	.0400	....	....	....	....	....	....
.410	.0457	.0456	.0432	.0426	.0499	....	....	....	....

The first curve to be discussed was nearly the last to be secured. The left eye was fatigued with the red light of wave length .740μ as bright as it could be obtained in the arc spectrum employed. The curve is shown in Fig. 1. There are three slight depressions of the abnormal curve below the normal, one occurring at each end, corresponding to the red and violet regions of the spectrum, and the third in the middle corresponding to the green. The depressions are not confined to the precise limits of these colors but extend into the surrounding regions. The conclusion is at once evident that the effect of fatigue of the left eye has been transferred to the right eye by some reciprocal or reflex visual process, and there results in an enhancement of the brightness of three spectral regions. The three depressions are separated by two coincidence points at about .64μ and .52μ, where the normal and abnormal curves coincide, or approach each other closely. The curve obtained when the fatiguing color was .690μ is shown in Fig. 2. The depressions are greatly deepened indicating that the reflex effect of this color is much greater than that of the

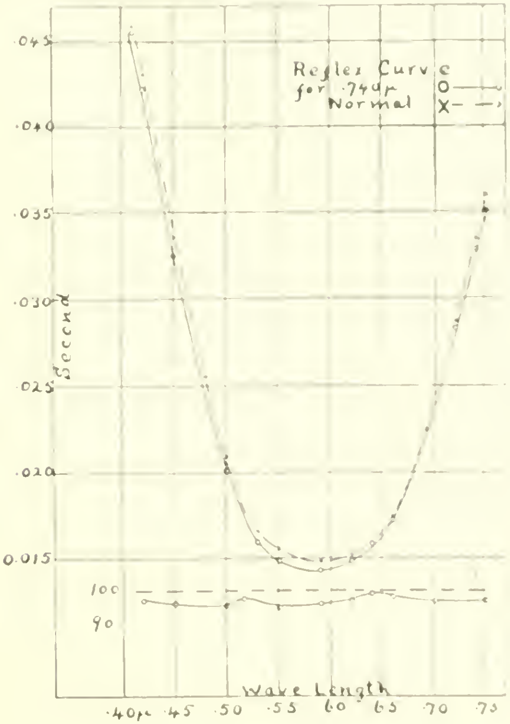

Fig. 1

Note. In most, and perhaps all, of the curves the greatest enhancement is complementary to the fatiguing color.

preceding. In Fig. 3 is shown the reflex curve for .687μ, which exhibits the maximum effect for red colors. The curve for the reflex effect of .677μ in Fig. 4 shows a diminution of the amount of enhancement of the brightness. These four curves are of the same type, but in addition to the varying magnitude of the reflex effects they show that the two coincidences of the curves do not occur at exactly the same points. We may conclude, however, that there are always two coincidences which occur near the wave lengths, .66μ and .50μ.

It now became of great interest to ascertain whether the transition colors would exhibit any reflex effects. The transition color .660μ was employed as the fatiguing stimulus with the result shown in Fig. 5. The curves coincide throughout their length showing that the brightness of the spectrum appears the same as when the eye is normal.

The narrowness of this peculiar region is well brought out by the fact that when the color .660μ was obtained from a spectrum formed by a single prism, slight depressions resulted. The single prism spectrometer with its insufficient dispersion of the red was therefore replaced by one with two prisms as described above.

As the peculiarity of the action of the transition colors is later explained as due to equilibrium between their direct and reflex effects, the transition points will subsequently be termed equilibrium points or colors.

In Fig. 6 the central portions of the above curves, together with that for .657μ, are shown together. The data are collected in Table 2. The reflex effect increases to a maximum for .687μ and thence falls off rapidly with increase of wave length to .740μ which is the longest wave studied. It seems probable that the reflex effects of still greater wave lengths would quickly become negligible, unless, indeed, there is an

TABLE 2. *Partial Reflex Curves*

λ	Normal	.657μ	.660μ	.677μ	.687μ	.690μ	.740μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.660μ	0.0174	0.0171	0.0173	0.0174*	0.0172	0.0172	0.0172
.640	.0159*	.0157	.0160*	.0156	.0151	.0156*	.0158
.620	.0152	.0149	.0154	.0148	.0141	.0147	.0148
.590	.0148	.0144	.0147	.0140	.0135	.0139	.0143
.550	.0155	.0150	.0152	.0148	.0142	.0146	.0148
.530	.0165	.0160	.0164	.0161	.0154	.0157	.0159
.500	.0209	.0212	.0207	.0212	.0208*	.0204	.0201

*Values not read, but obtained from full curves.

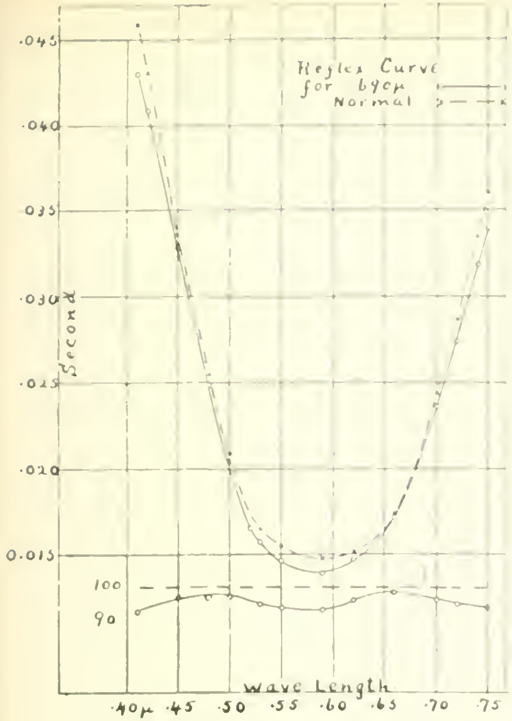

FIG. 2

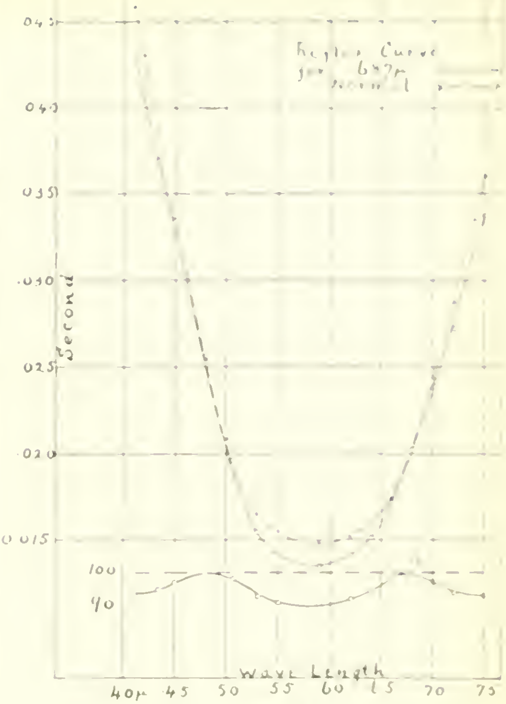

FIG. 3

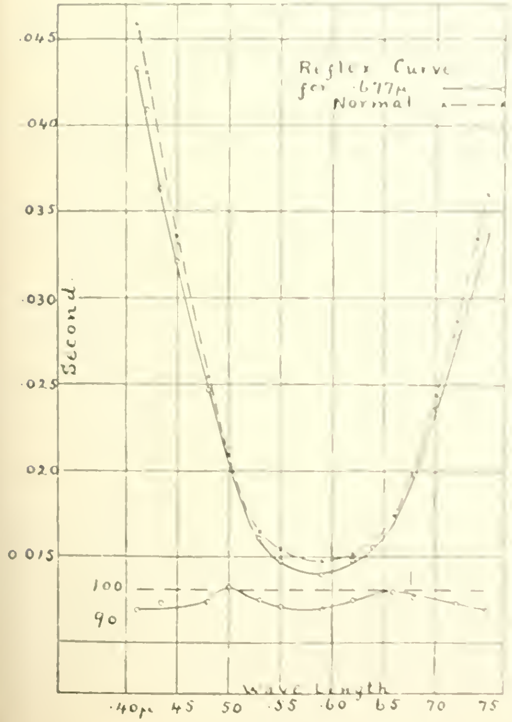

FIG. 4

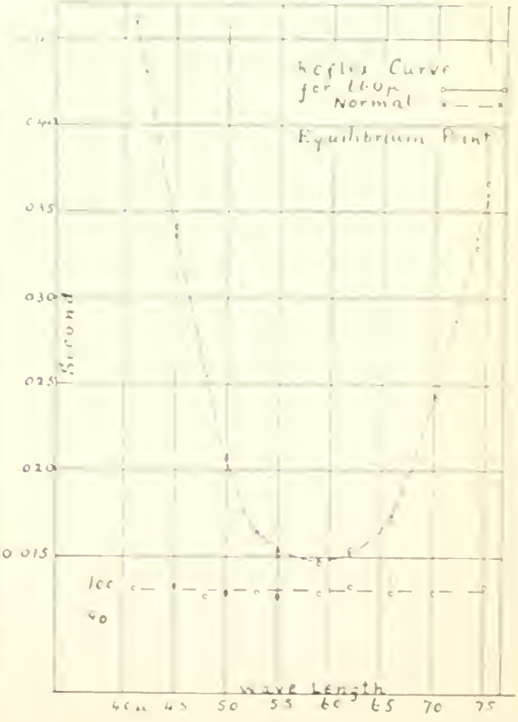

FIG. 5

equilibrium point at some region beyond, a supposition to which no support is given by the sensation curves of Abney and of König, Fig. 34. This diminishing reflex effect with increasing wave length affords an explanation of certain interesting experiments of Edridge-Green, which are later discussed.

The reflex effect of the fatiguing color .625μ is shown in Fig. 7. The three depressions in the curve, corresponding to the ends and middle of the spectrum are well exhibited, and the coincidences as before are at the wave lengths .66μ and .50μ. There can be no doubt that the reds whose reflexes were just studied are simple colors, and that the color .625μ is compound. Yet the same reflex depressions occur for both. Since red affects all three color sensations that are possible according to the three-component theory, a compound color, .625μ, can affect no more. The inferences to be drawn from the curves in question are therefore not contradictory.

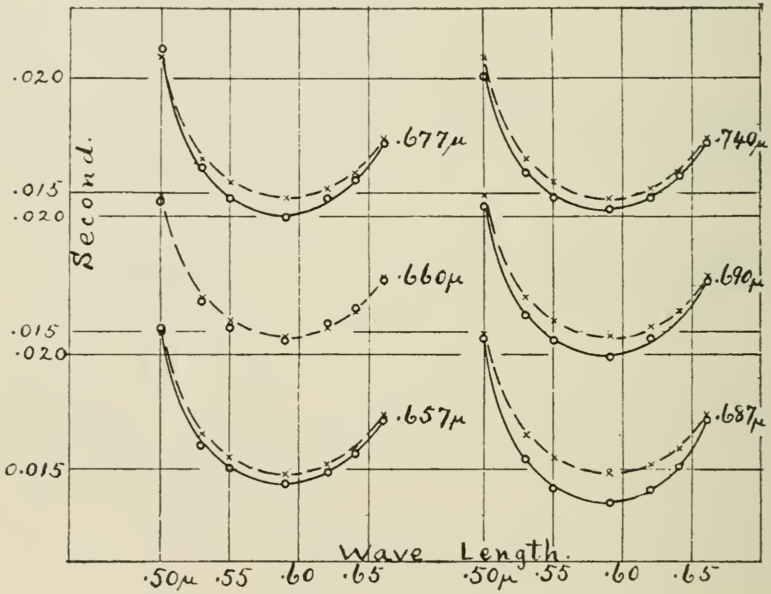

FIG. 6. *Partial Reflex Curves.*

In Fig. 8 the reflex effect of .577μ is displayed. This is near the brightest part of the spectrum, which probably accounts for the large reflex effect obtained. There are two well marked depressions; but the larger, extending from the coincidence point .48μ to the end of the red, has a slight indication of a division into two parts.

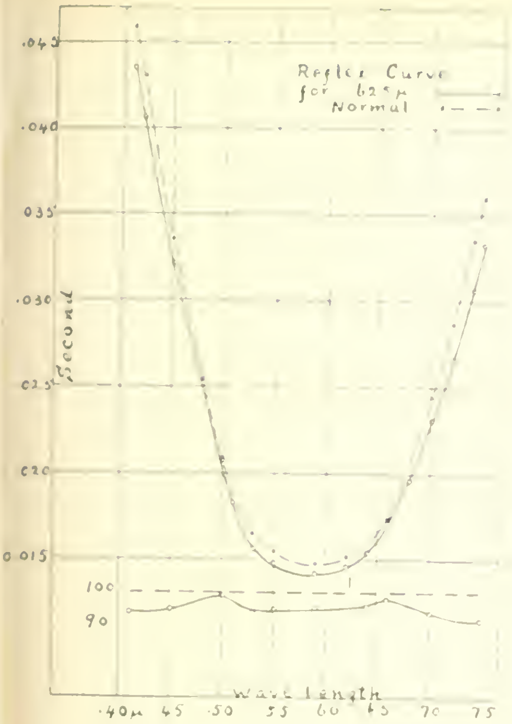

Fig. 7

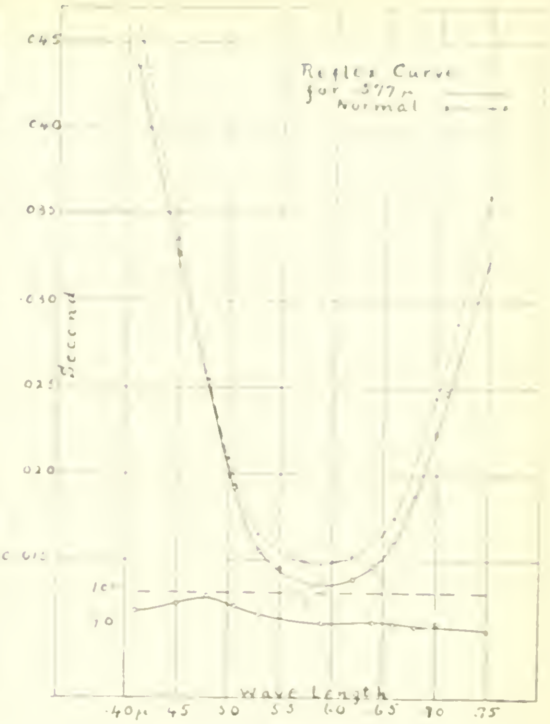

Fig. 8

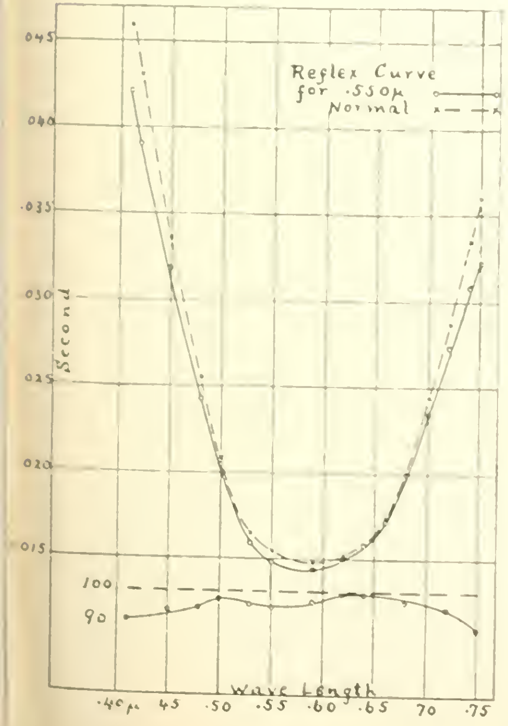

Fig. 9

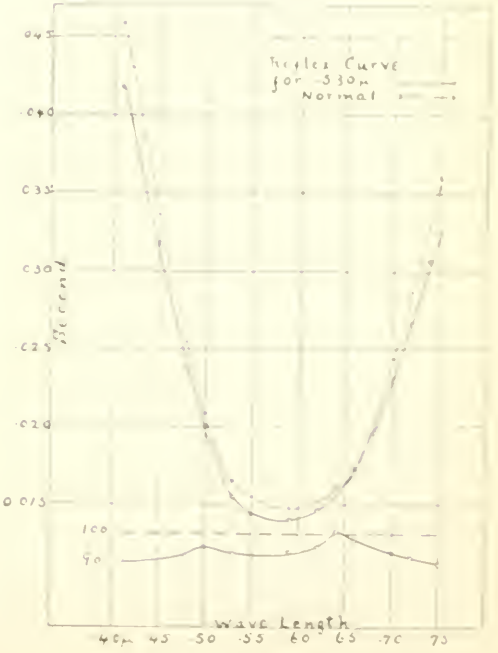

Fig. 10

The second equilibrium color .570μ was then made the fatiguing stimulus and a curve similar to that in Fig. 5 obtained.[8] As with the preceding equilibrium point, complete coincidence with the normal resulted.

In Figs. 9 and 10 are shown the reflex effects obtained with the fatiguing colors .550μ and .530μ respectively. As is to be expected, both curves are of the same type, with the three well marked depressions separated by the coincidence regions .66μ and .50μ. The magnitude of the reflex effects is noticeably greater for the shorter wave than for the longer.

In the paper[9] on the discovery of the transition points, it was found that a transition region extended from about .460μ to .480μ. This was considered to be due to the wide dispersion of the blue in the prismatic spectrum. If that explanation were true, the transition or equilibrium region in the violet should possess a still greater width. This was found not to be the case.

A study of the sensation curves of Abney and of König, Fig. 34, suggested a better explanation. The region lying between .480μ and .520μ is visually by far the most complex in the spectrum, as the sensation curves there have two, and according to some three, intersections, and the curve for red has in that neighborhood also its more refrangible end. It seemed probable therefore that two or possibly three additional equilibrium points might exist close together. As a strongly marked reflex depression always occurs in the green-yellow part of the spectrum, which is also the easiest to measure with accuracy, a series of partial curves for thirteen colors extending from .495μ to .523μ, inclusive, was obtained in a short time. The data for these are given in Table 3 and the curves are all plotted in Fig. 11. The results verified the anticipation. Two additional equilibrium points were discovered at the wave lengths .520μ and .505μ, and the previously known equilibrium point at .480μ was verified. Full persistency curves were now made for each of these colors, which are similar to that in Fig. 5. These curves are completely coincident with the normal.

The effects of the intermediate colors .515μ and .495μ were then investigated with the results shown in Figs. 12 and 13. In both curves are seen the three familiar depressions, and the two coincidence points situated as before. It is especially to be noted that no new parts of the spectrum are enhanced in brightness.

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[8] As all curves obtained with the equilibrium colors are coincident with the normal, only that in Fig. 5, for .660μ, is shown.

[9] Phil. Mag. *38*, p. 69; 1919.

The reflex effects of the two colors .460μ and .450μ are given in Figs. 14 and 15, respectively. The three depressions and the two coincidence points occur as before.

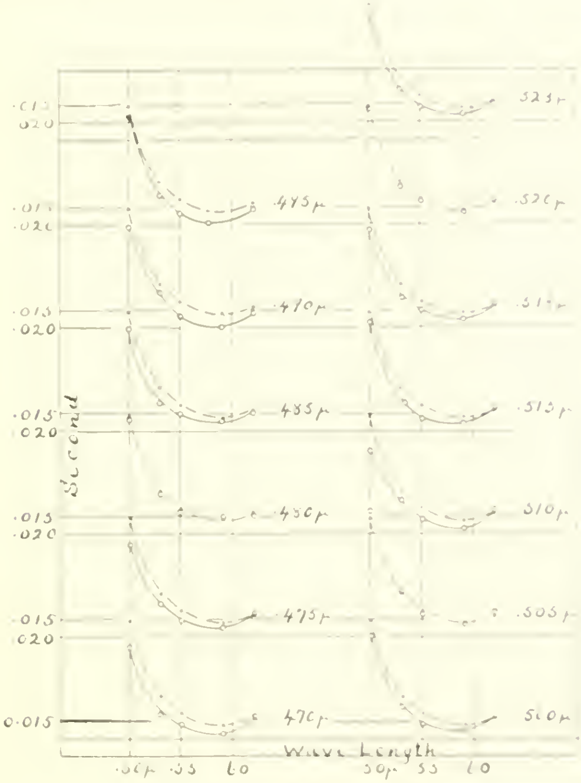

FIG. 11. *Period [illegible] Curves.*

The last equilibrium color as previously determined was of the wave length .420μ. This was now examined for its reflex effect. The curve is shown in Fig. 16. Three small depressions are produced. The color .425μ was then employed with the result that this was proved to be the real equilibrium point. The curve is like that in Fig. 5. As the original points were discovered when darkness adaptation affected fatigue, the discrepancy in the determination of this point, and also in the result for .460μ, seems fully explained.

The last color to be discussed is the violet of wave length .410μ. Some curiosity was aroused as to whether it would show any reflex

TABLE 3. *Partial Reflex Curves*

λ	Normal	.470μ	.475μ	.480μ	.485μ	.490μ	.495μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.620μ	0.0152	0.0152	0.0153	0.0151	0.0151	0.0148	0.0148
.590	.0148	.0143	.0145	.0148	.0146	.0140	.0141
.550	.0155	.0148	.0149	.0153	.0150	.0146	.0146
.530	.0165	.0154	.0159	.0163	.0156	.0160	.0157
.500	.0209	.0193	.0193	.0206	.0199	.0198	.0204

λ	.500μ	.505μ	.510μ	.515μ	.518μ	.520μ	.523μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.620μ	0.0154	0.0153	0.0153	0.0153	0.0152	0.0154	0.0150
.590	.0144	.0148	.0143	.0144	.0144	.0147	.0144
.550	.0149	.0153	.0148	.0147	.0150	.0153	.0148
.530	.0158	.0165	.0159	.0156	.0157	.0161	.0158
.500	.0200	.0213	.0188	.0202	.0196	.0207	.0203

effects at all, on account of its low intensity, which the luminosity measurements of Abney[10] show to be about one seven-hundredth of the brightness of yellow. The result given in Fig. 17 was most surprising. Two very large reflex depressions were obtained, the larger of which covering the more refrangible part of the spectrum from the coincidence point at .66μ is partly divided into two smaller ones at the second coincidence point .50μ.

A comparison of the curves for .410μ and .577μ, Figs. 17 and 8, shows that, so far as luminosity is concerned, violet is quite seven hundred times as powerful as yellow in exciting reflex effects. This is probably explanatory of the conclusions of Rood[11] in respect of complementary colors: "A violet which appears to the eye quite dark, is able to balance a bright greenish-yellow and form with it, white, and the same is true of ultra-marine blue and yellow. There is another way of stating these facts: we can say that in mixtures, violet has a greater power of saturation than any of the colors; next follows ultra-marine blue; then red and cyan-blue about the same, then orange and green about the same, and finally, yellow."

In Fig. 18, the reduced curves at the bottom of each figure including all the equilibrium curves, are gathered together. Each fatiguing color is indicated by a small vertical line below the corresponding curve.

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[10] Abney: "Researches in Colour Vision." p. 94.

[11] "Modern Chromatics," p. 165.

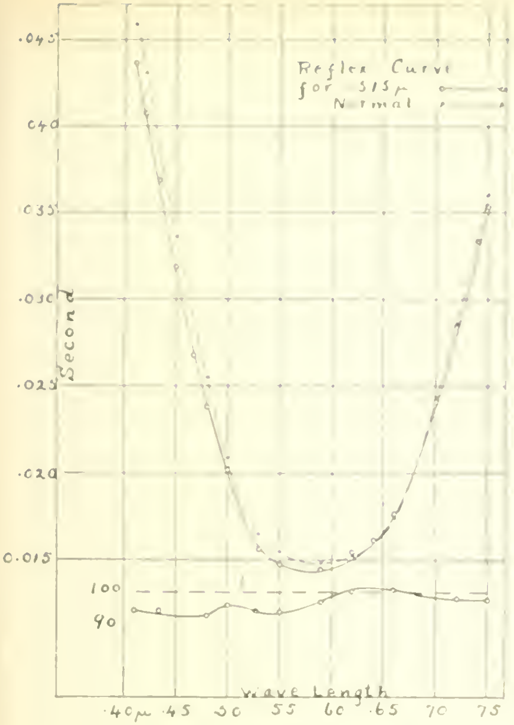

FIG. 12

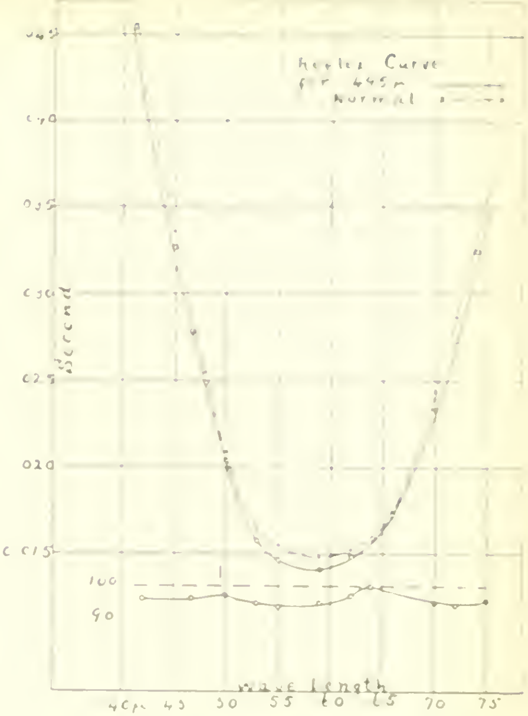

FIG. 13

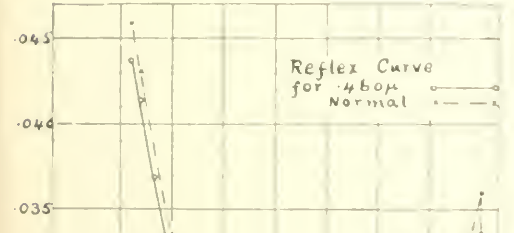

FIG. 14

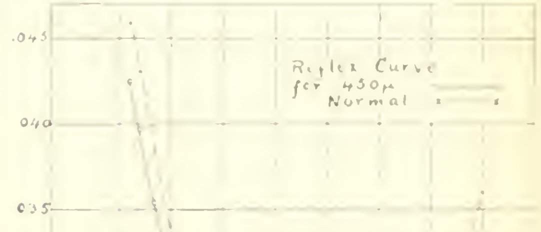

FIG. 15

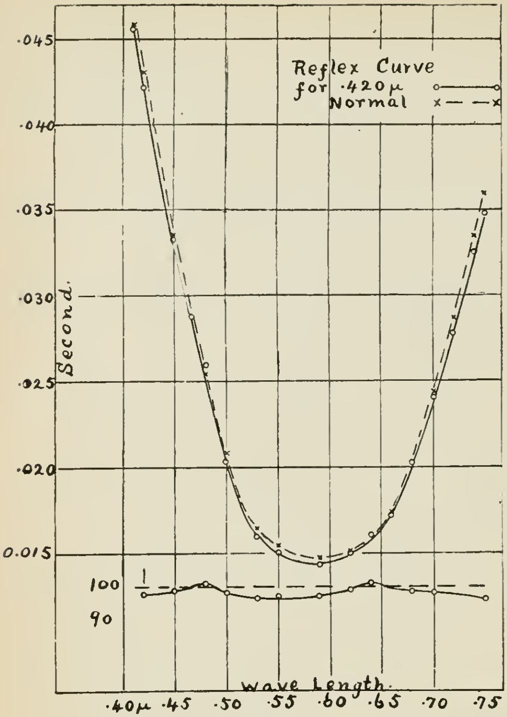

FIG. 16

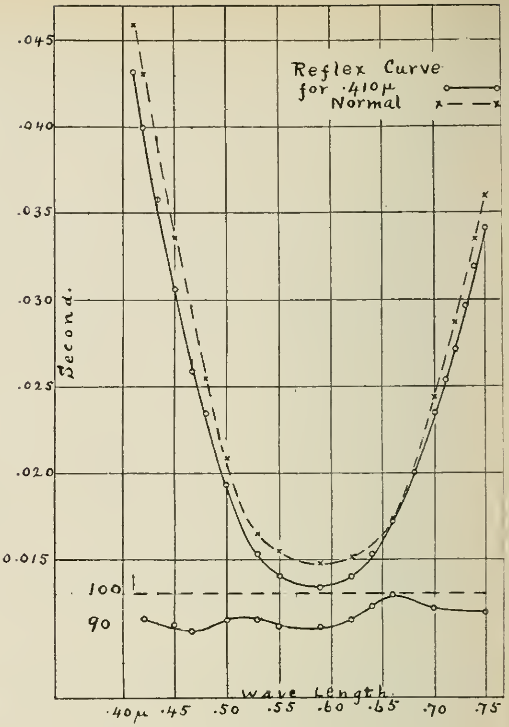

FIG. 17

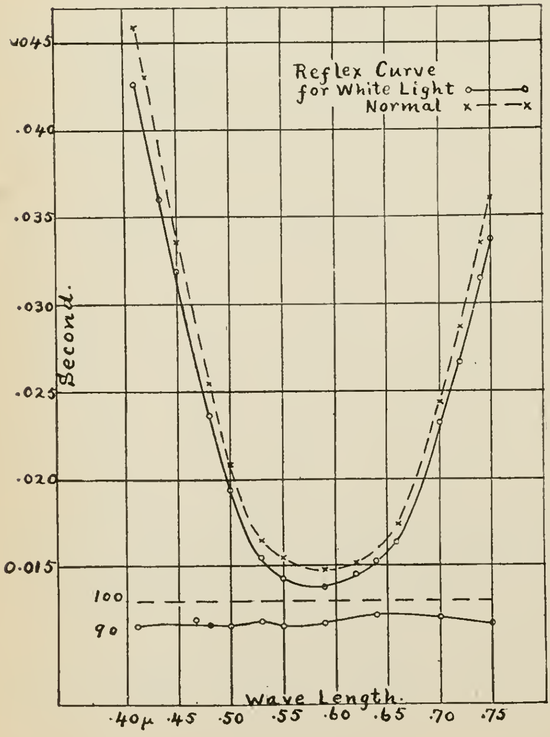

FIG. 19

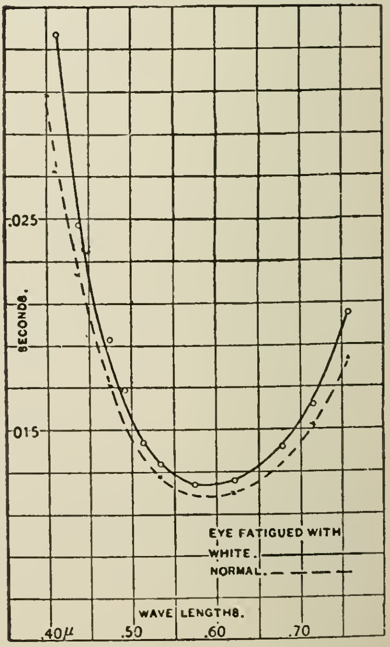

FIG. 20

The depressions and coincidences are all seen together and the general uniformity in extent and position is evident. The relative depths of the depressions probably indicate the magnitude of the reflex process, but this cannot be fully appreciated unless it can be connected with the luminosity or the wave length of the colors, or with both.

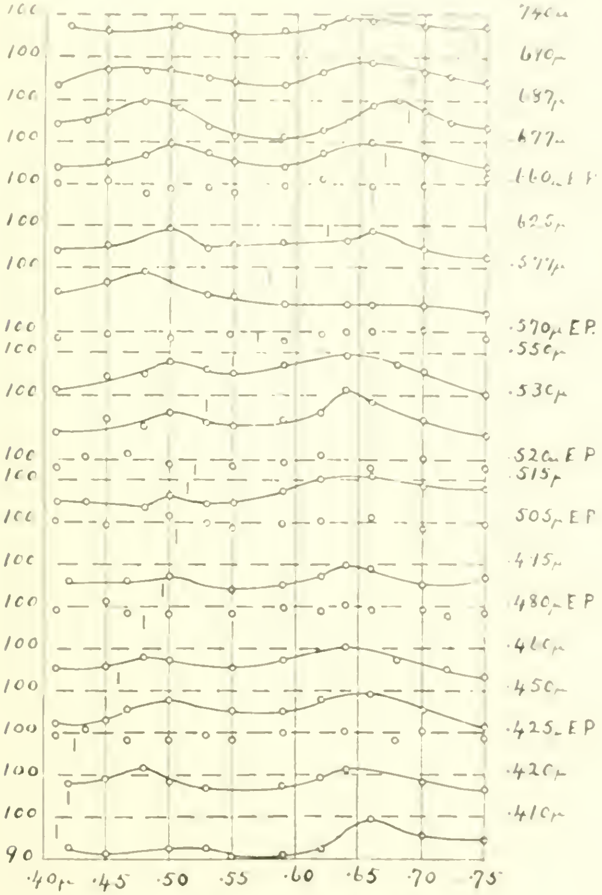

Fig. 18. *Reduced Reflex Curves.*

In these experiments the fatigue was isolated in one eye, and the reflex effects, which occur in both, were isolated in the other, and therefore can be studied by themselves. We are justified in concluding that every ray of light excites in the visual apparatus reciprocal or reflex effects which enhance the brightness of three parts of the spectrum corresponding to red, green, and violet. It is probable that the relative actions on the three sensations vary with the exciting color, and range from the pronounced effects described in these experiments to the refined gradations accompanying the most delicate shades of color. The magnitude of the reflex sensations seems to be proportional to some extent to the luminosity of the color stimulus, but varies to a far greater extent inversely as some function of the wave length. The strong reflex effects of the violet probably merge gradually into the painful and destructive action which ultra-violet waves exercise on the retina.

If all the reflex curves were to be plotted together, the resultant might be interpreted as the effect to be produced if white light were used for the purpose of fatigue. This experiment was tried with white light and the curve in Fig. 19 plotted from the measurements obtained. The whole curve lies below the normal, indicating that the reflex effect of white light enhances the brightness of all parts of the spectrum. The reduced curve in the lower part of the figure has three slight depressions which show that white light recognizes, as it were, the three color sensations. Possibly this result may have some bearing on the question as to whether white light is a mixture of color waves or an irregular disturbance in the ether which is resolved into periodic elements by the prism. Such evidence as these curves afford inclines to the former view.

III. FATIGUE CURVES

It seemed incredible that reflex effects of such magnitude as have just been described should not betray themselves in the same eye that was fatigued. Yet the numerous curves previously published and referred to above in Section I, were apparently devoid of reflex depressions. While the preceding experiments were in progress, it was recalled that in the author's[12] first paper on color vision very slight depressions had been found and commented upon as possibly indicative of enhancement of sensations. With one exception, the green, they were too small to be of evidential value, and they were gradually forgotten. As the former experiments were made with the unfatigued eye in darkness adaptation, it was finally suspected that darkness itself produced a reflex effect, or something analogous to it, which diminished rather than enhanced the brightness of colors. Certain curves exhibiting the effect of darkness had previously been obtained,[13] here reproduced in

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[12] Phys. Rev. *11*, 274; 1900.

[13] Phys. Res. *11*, p. 265; 1900.

Fig. 33, which showed effects of about the same magnitude as the reflex depressions, but acting in opposition to them. It seemed likely therefore that darkness adaptation of one eye had masked or balanced the reflex action of light in the other.

TABLE 4.—*Fatigue Curves*

λ	Normal	687μ	670μ	660μ	589μ	570μ	550μ	530μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.750μ	0.0360	0.0382	0.0391	0.0358	0.0374	0.0353	0.0310	0.0321
.740	.0335	.0356	.0362	.0338	.0351	.0332	.0293	.0300
.720	.0287	.0299	.0311	.0282	.0297	.0289	.0248	.0264
.700	.0244	.0261	.0261	.0237	.0260	.0245	.0215	.0228
.680	.	.0205	.0214	.	.0218			.0192
.660	.0174	.0176	.0181	.0173	.0184	.0171	.0166	.0170
.640	.	.0160	.0163	.0160	.0160	.0157	.0156	.0158
.620	.0152	.0149	.0148	.0151	.0154	.0150	.0151	.0153
.590	.0148	.0141	.0144	.0147	.0157	.0146	.0150	.0151
.550	.0155	.0147	.0151	.0157	.0175	.0154	.0169	.0166
.530	.0165	.0156	.0159	.0163	.0183	.0167	.0182	.0183
.500	.0209	.0206	.0208	.0207	.0204	.0204	.0202	.0207
.480	.0255	.0254	.0254	.0251	.0241	.0250	.0230	.0233
.450	.0336	.0326	.0329	.0333	.0321	.0328	.0305	.0310
.433		.0372	.0380	.0393	.0365	.0384	.0342	.0362
.420	.0431	.0411	.0414	.0429	.0413	.0427	.0407	.0398
.410	.0459	.0440	.0442	.0465	.0440	.0470	.0436	.0428

λ	520μ	515μ	505μ	495μ	480μ	450μ	425μ	410μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.750μ	0.0362	0.0342	0.0354	0.0341	0.0361	0.0325	0.0362	0.0342
.740	.0335	.0319	.0328	.0321	.0333	.0305	.0337	.0319
.720	.0282	.0273	.0284	.0275	.0286	.0271	.0286	.0278
.700	.0250	.0235	.0243	.0234	.0247	.0236	.0243	.0238
.680	. . . .	. . . .	. . .	.	.			.0194
.660	.0173	.0177	.0174	.0168	.0171	.0181	.0175	.0172
.640	.0162	.0164	.0163	.0155	.0163	.0168	.0162	.0159
.620	.0151	.0157	.0152	.0147	.0154	.0159	.0155	.
.590	.0148	.0153	.0147	.0142	.0148	.0153	.0149	.0142
.550	.0155	.0160	.0154	.0145	.0154	.0162	.0153	.0146
.530	.0166	.0171	.0162	.0155	.0165	.0168	.0166	.0157
.500	.0202	.0205	.0204	.0200	.0210	.0214	.0205	.0206
.480	.0258	.0241	.0252	.0242	.0252	.0267	.0259	.0270
.467	. . . .	.0270		.0290	. .			.0304
.450	.0332	.0315	.0335	.0349	.0341	.0351	.0340	.0367
.433	. .	.0365	. .	.0414	. .	.0411	.	.0420
.420	.0430	.0399	.0428	.0454	.0435	.0466	.0431	.0459
.410	.0460	.0427	.0467	.0488	.0467	.0502	.0456	.0491

A new set of persistency curves was next obtained with the right eye in a state of fatigue and at the same time the left maintained in daylight adaptation. The results completely verified the anticipation, and supplement in a remarkable way those curves already described.

The first color used to fatigue the eye was red of wave length $.687\mu$. The measurements are given in Table 4 with those for all the curves of this series. The results are shown in the curve in Fig. 21. The fatiguing action produced an elevation in the part corresponding to red, and two reflex depressions in the parts corresponding to violet and green. Two coincidence or intersection points are found as before at the same wave lengths $.66\mu$ and $.50\mu$. Since red light also produces a reflex enhancement of the red, the elevation is the algebraic sum or the net result of fatigue and reflex action, the balance being in favor of the fatigue. Red light fatigue therefore diminishes the brightness of red, but increases the brightness of both green and violet. In Fig. 22 the curve for the fatiguing color $.670\mu$ is shown, which resembles the preceding so closely as to need no comment.

The equilibrium color $.660\mu$ resulted in a curve, Fig. 23, which coincides with the normal. This was also the case with the equilibrium color $.570\mu$.[14] The observations made after fatiguing with the intense middle colors of the spectrum were at times rendered troublesome by the after images. In various ways these difficulties were surmounted and consistent readings obtained.

Only one color between the first two equilibrium points seemed necessary; that chosen was $.589\mu$, the curve for which is shown in Fig. 24. This is characterised by two prominent elevations in the red and green, and a reflex depression in the violet. The coincidence points are at nearly the same places as before. Since the charactertistic effect of fatigue is a diminution of brightness, elevations will always indicate what sensations are directly, and depressions what are reflexly affected. Yellow light therefore directly stimulates the red and green sensations, and by the sensory reflex process, the violet.

Two colors in the green were used, $.550\mu$ and $.530\mu$, the curves for which are shown in Figs. 25 and 26. The effects produced are identical, consisting of an elevation in the green and depressions in the red and violet. The points of coincidence or intersection are about the same as before.

[14] As all the equilibrium colors give curves coincident with the normal, only that for $.660\mu$ is here reproduced.

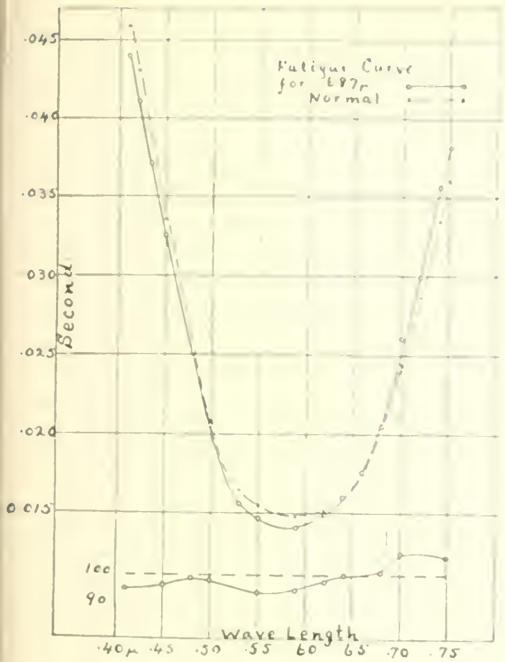

FIG. 21

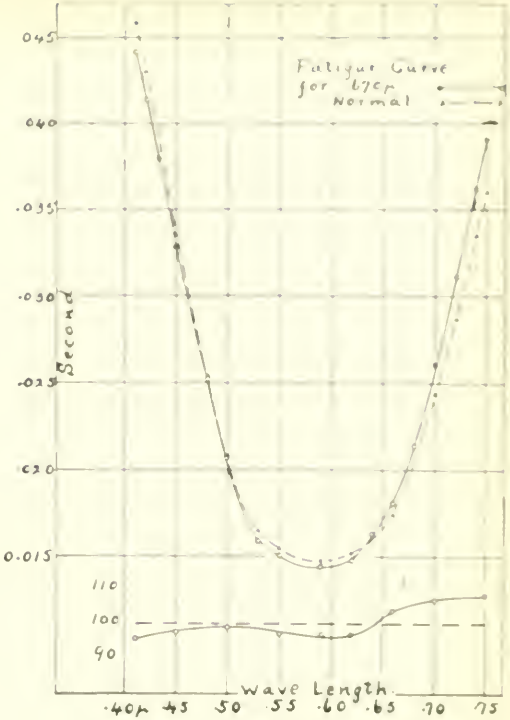

FIG. 22

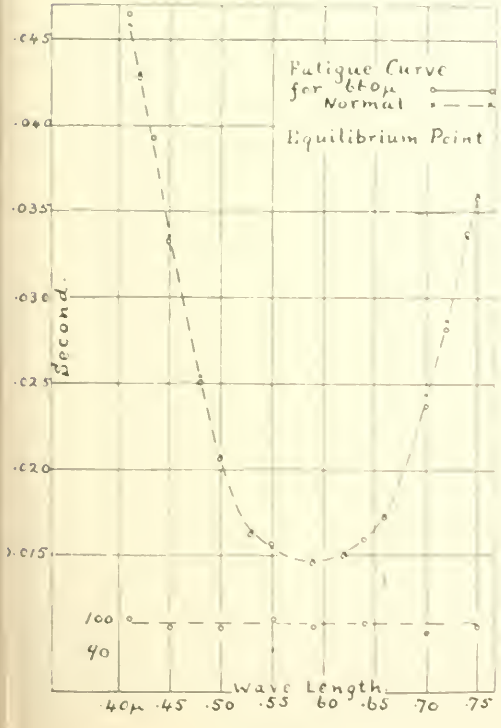

FIG. 23

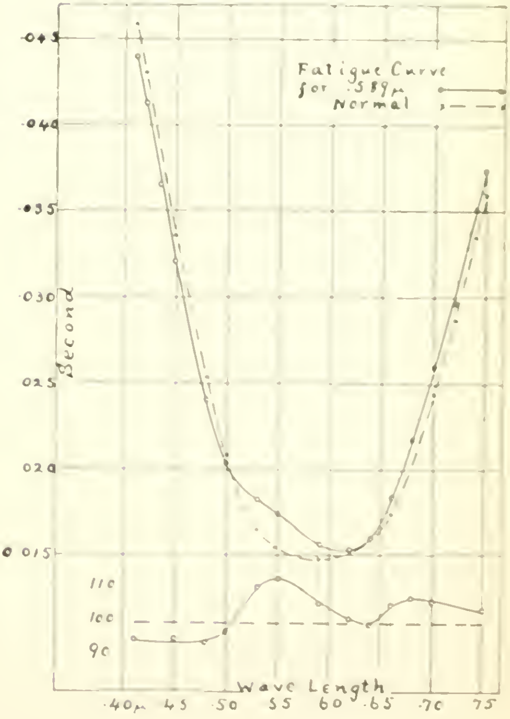

FIG. 24

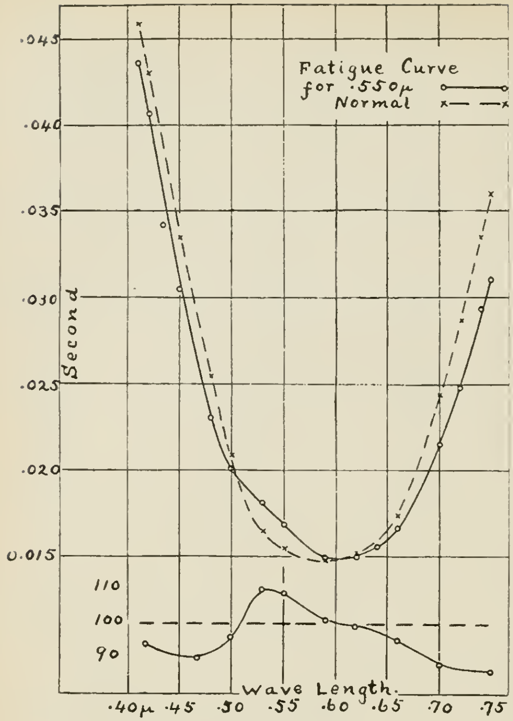

FIG. 25

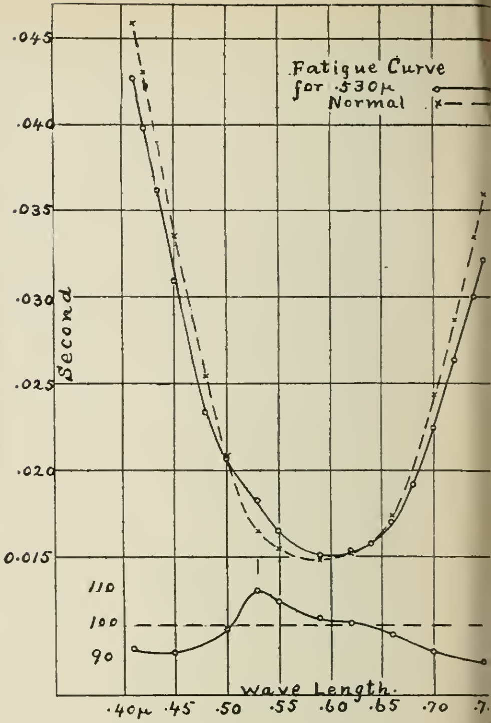

FIG. 26

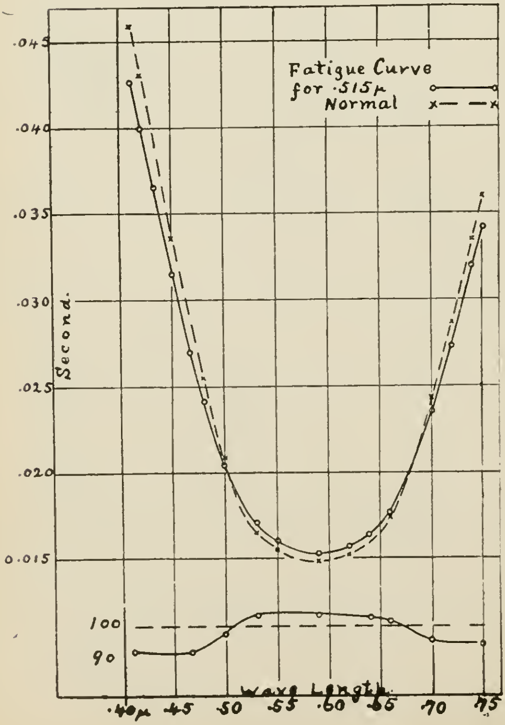

FIG. 27

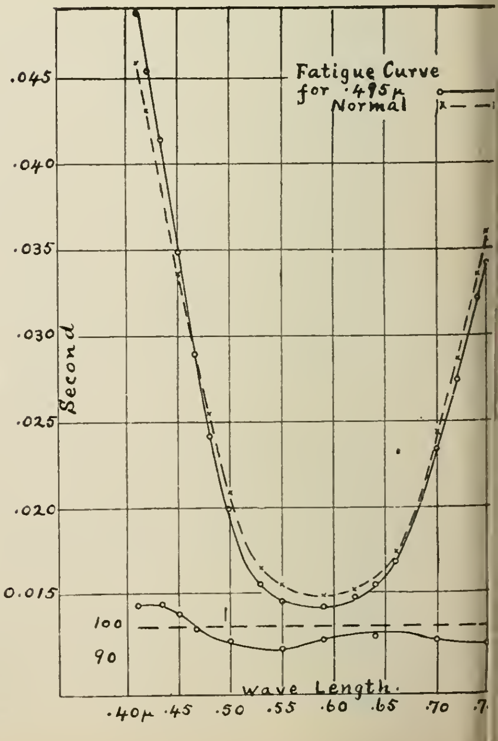

FIG. 28

The equilibrium colors previously found at .520μ, .505μ and .480μ, proved to have the same character when used directly. The corresponding curves are similar to that in Fig. 23.

The curves for the fatiguing colors .515μ and .495μ, between these equilibrium points, are plotted in Figs. 27 and 28. They are especially to be noted. All curves from the red to .515μ, inclusive, have elevations only in the red or green, or in both. The violet is affected always so as to produce a reflex depression. Beginning with .495μ, the remainder of the curves show an elevation in the violet, indicating this color sensation to be directly stimulated. The curve for .495μ is almost identical with that for violet of wave length .410μ, as shown in Fig. 30. Both have depressions in the green and red portions of the curve. The direct effect of the color .515μ is evidently in the green while on the more refrangible side of the equilibrium point .505μ, violet is the sensation directly excited. An examination of this region in the sensation curves of Abney and of Konig, Fig. 34, indicates that, at the intersection of the green and blue (or violet) sensation curves a very small change of wave length transfers the predominating stimulus from green to violet. It will be seen later that the equilibrium color .505μ is probably identical with this intersection point. It follows therefore that these persistency curves are in close harmony with the sensation curves.

From Fig. 29 it is seen that the effect of the fatiguing color .450μ is to cause elevations in the violet and green regions and a depression in the red. This indicates that by this color the two sensations, green and violet, are both directly stimulated, while the red is enhanced by the reflex process. The evidence from Fig. 28 that the color .495μ, which lies between the green and .450μ, does not directly affect the green sensation, but only reflexly, is a most unexpected result for which the author has no explanation. It is quite possible from the sensation curves of Abney and of König, that for a short distance in this region of the spectrum the red and green sensations nearly balance each other.[15] In this characteristic of the sensation curves the explanation may lie. Notwithstanding the somewhat minute analysis of this part of the spectrum described in this paper, further investigation of this peculiarity is necessary.

The effect of the remaining equilibrium color .425μ shows coincidence with the normal throughout, as in Fig. 23.

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[15] See especially Exner's Sensation Curves in Parsons', Colour Vision, p. 223.

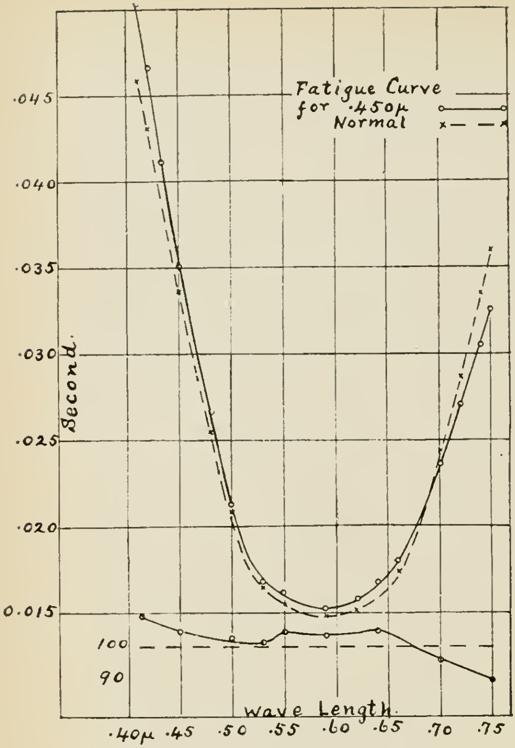

FIG. 29

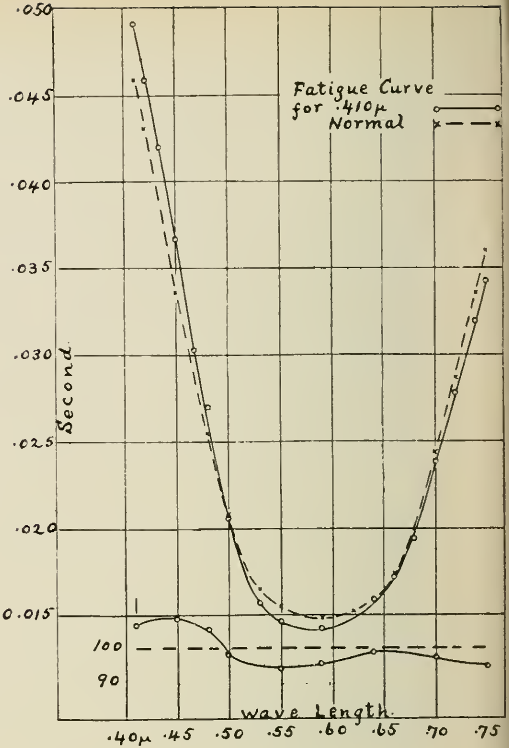

FIG. 30

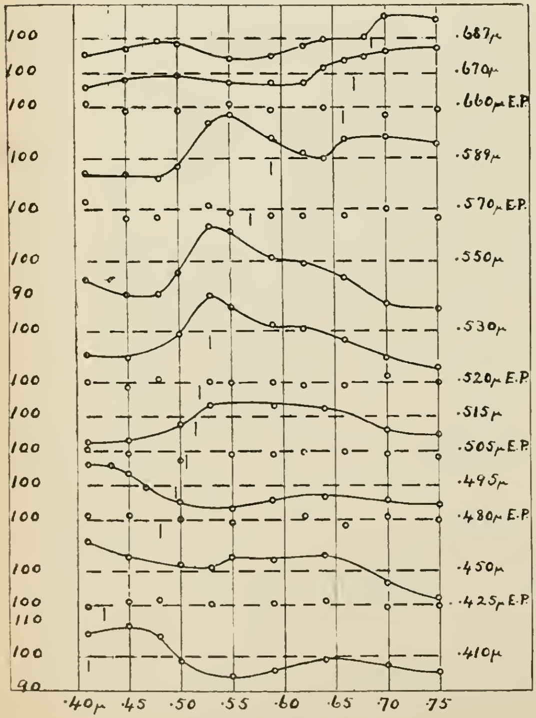

FIG. 31. *Reduced Fatigue Curves.*

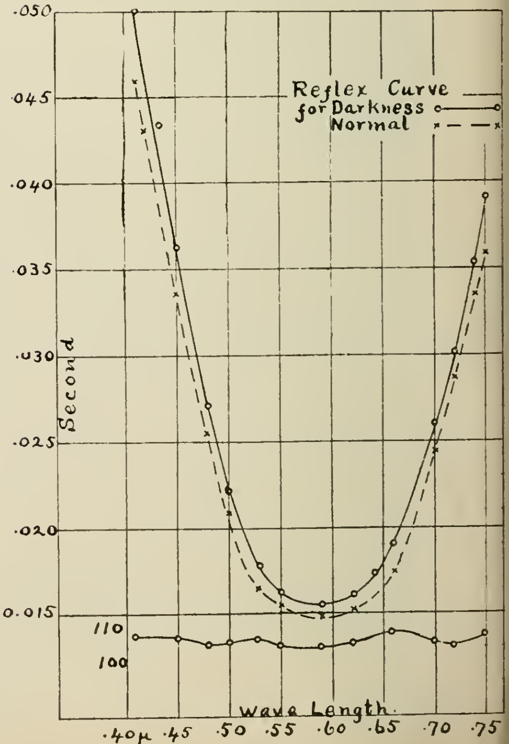

FIG. 32

The reduced fatigue curves are all shown together in Fig. 31, which displays comprehensively the normal curves, the elevations and depressions of the fatigue curves, the intersection points, and the fatiguing colors indicated by short vertical lines below each normal.

From a former paper[16] there is reproduced in Fig. 20, the persistency curve obtained when the observing eye was fatigued with white light. This curve lies above the normal in all parts indicating fatigue of all the sensations. No indication of a division into three elevations is found. If this curve be compared with the reflex curve for white in Fig. 19, the opposite character of the two actions will at once be evident.

The above curves show that the red, green, and violet colors produce one elevation in the corresponding part of the spectrum, and two depressions in the parts of the spectrum corresponding to the other two sensations. The yellow and blue colors produce two elevations, the former in the red and green regions, the latter in the green and violet, and a single depression in the part corresponding to the remaining sensation. No color was found that produced elevations simultaneously in the red and violet. Abney[17] came to the conclusion that the sensation of violet was compounded from the red and blue sensations. The evidence presented by both sets of curves in this paper is completely against that view, and it seems impossible to avoid the conclusion that violet is a simple sensation. The compound character of yellow and blue is abundantly confirmed.

It was stated above that the effect of darkness adaptation of the left eye might be transferred to the right (or *vice versa*) and so balance and thereby conceal the reflex effect of whatever color stimulus was applied. In order to prove this, a curve was obtained by the right eye in normal daylight adaptation, the left eye being kept blindfolded for about three hours, while the measurements were made. The data are given in Table I and the curve is shown in Fig. 32. This lies wholly above the normal, showing that the effect of darkness adaptation is transferred from one eye to the other, and diminishes the brightness of all color sensations, an effect just the opposite of that shown for white light in Fig. 19. The reduced darkness curve in Fig. 32 shows evidence of three depressions, and thereby adds its testimony to the threefold character of color vision.

From a former paper[18] there is reproduced in Fig. 33, a set of curves obtained under different conditions of darkness adaptation. In this figure the curves marked "a" and "b" were obtained by the right eye, when both were under the influence of very dim light or darkness. The curve "c" was obtained when the right eye was blindfolded and the left was in daylight adaptation. The curve "d" is the normal.

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[16] Phys. Rev. *11*, p. 276; 1900.

[17] Researches in Colour Vision, p. 230. Also, Phil. Trans. A *193*, p. 259.

[18] Phys. Rev. *11*, p. 265; 1900.

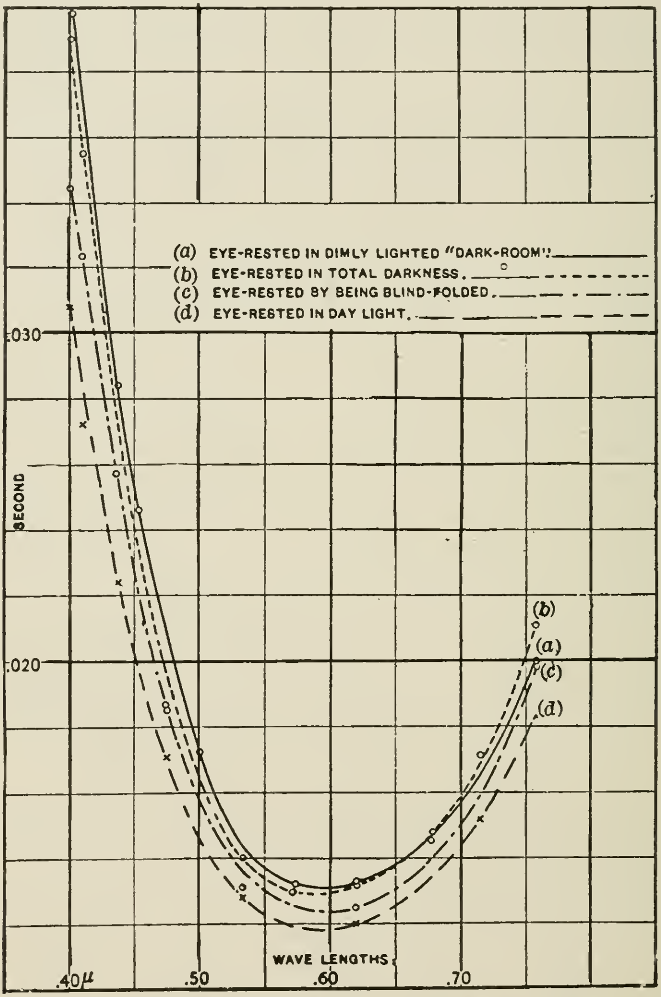

FIG. 33. *Curves showing various degrees of darkness adaptation.*

Under all conditions therefore the effect of darkness adaptation is precisely the same in character, though not in magnitude.

Since darkness adaptation always diminishes the brightness of all colors, it may be questioned whether darkness makes the eye more sensitive, as is usually stated. From these experiments it seems reasonable to hold that the effect of prolonged darkness adaptation is to give time for all direct and reflex effects of light—some of which according to Burch,[19] last for quite two hours—to disappear from the visual apparatus. Very feeble rays of light will therefore become perceptible as there is nothing present in the retina to interfere with them. It must be remembered, however, that the curves described in this paper are for bright colours which involve the photopic mechanism of the eye, and the results may not be valid for the scotopic mechanism if such exists.

The experiments on darkness are susceptible of another and probably a more rational explanation, which does not attribute to darkness a positive action. We have seen that the effect of white light fatigue on one eye is just the opposite of its reflex effect from the other. The normal condition of the retina, as experiment shows, is obtained when daylight is admitted to both eyes simultaneously. But daylight must exercise some effect, both of fatigue and reflex action. By blind-folding one eye, the white light is thereby excluded and prevented from having its reciprocal or reflex effect. The apparent reflex effect of darkness is therefore merely due to protection from the real effect of white light.

From the results of these measurements, it is evident how extraordinarily far from correct is Charpentier's[20] conclusion that darkness adaptation of one eye has no effect on the other, reliance upon which has probably invalidated many measurements of color.

On reference to the darkness adaptation curves in Fig. 33, it will be observed that the maximum effect in diminishing the physiological brightness of the spectrum is not obtained by blind-folding the eye or by keeping it in complete darkness, as would quite naturally be expected, but by adapting the eyes for light of very low intensity, such as that in a dimly lighted dark room. The dark room used in this experiment was painted black and the only illumination was the light escaping from the screens around the acetylene flame. The curve "c" for the blind-folded eye is about half way between the normal "d," and the curve "a" for the eye adapted for weak light.

This unexpected peculiarity serves to explain an observation by Fechner which is thus described by Edridge-Green[21]: "In certain conditions the additional stimulation of one eye with light not only causes no sensation of increased brightness but the reverse. This is illustrated by Fechner's paradoxical experiment. One eye is directed to an illuminated surface, as for instance a sheet of white paper, whilst the other eye is closed. If the closed eye be suddenly opened behind a sheet of smoked glass, the field of vision will appear distinctly less bright."

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[19] Proc. Roy. Soc. B. *76;* 1905.

[20] Parsons: Colour Vision, p. 50.

[21] Physiological Optics, p. 127.

From the curves it is seen that blind-folding or closing one eye will diminish the brightness of the white surface to the other. When weak light coming through the smoked glass is then admitted to the previously closed eye, a still further diminution of the brightness of the white light ought to result, which is what Fechner observed. Fechner's experiment therefore follows logically from the evidence of the curves, and ceases to be paradoxical when the comparative effects of weak light and darkness upon the visual apparatus are more perfectly understood.

In Fig. 34, the sensation curves[22] of König and of Abney are shown with the six equilibrium points marked. The occurrence of these points at the ends and intersections of the sensation curves is of great interest. The actual wave lengths of the intersections for different observers are given by Parsons[23] in the following table, to which four of the equilibrium points are added by the author:

	a	*b*	*c*	*d*
König (sunlight)	573	503	496	450
Exner (arc light)	577	508	494	475
Abney (arc light)	577.2	515	500	...
Equilibrium points (arc light)	570	520	505	480

The equilibrium point $.480\mu$ is probably not the intersection point "d," the existence of which Abney's curves do not confirm, but rather the end of the sensation curve for red. The agreement of the author's values with those of Abney is quite good.

Since the six equilibrium points apparently produce neither direct nor reflex effects, we may interpret this as an equilibrium between the two actions, or possibly as a balance between excitation and inhibition.

The two mean points of coincidence with the normal which nearly all the curves exhibit, are, for the fatigue curves, $.648\mu$ and $.50\mu$, and for the reflex curves, $.658\mu$ and $.502\mu$. The further mean value $.653\mu$

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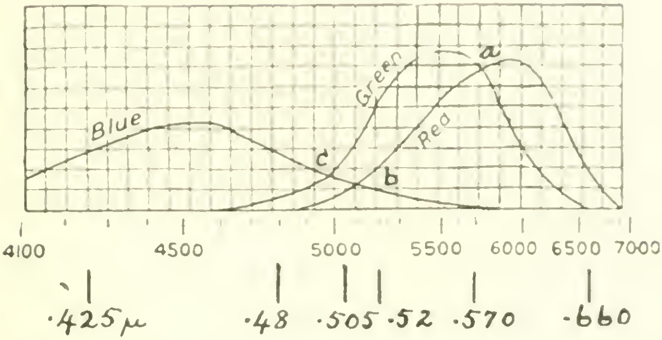
[22] Parsons: "Colour Vision," pp. 222 and 244. See also Exner's curves on p. 222 for intersection point "d."

[23] Parsons: loc. cit. p. 230.

is near the equilibrium point .660μ and may be identified with b. The second is almost the mean of the three equilibrium points .480μ, .505μ and .520μ.



Normal Sensation Curves. (Abney and Watson.)

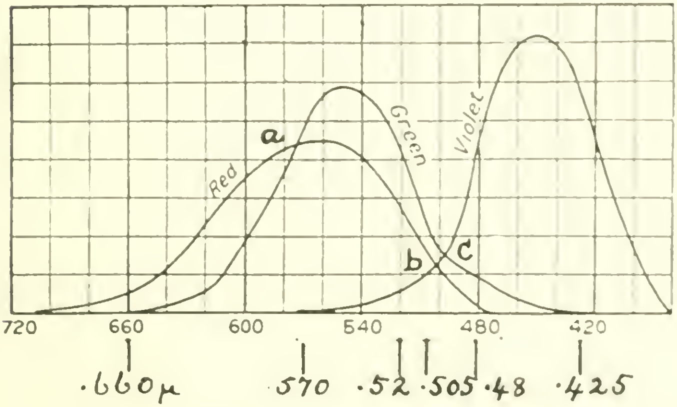


Fig. 34. Sensation Curves. (König and Dieterici.)

IV. THEORETICAL APPLICATIONS

From the experimental results which have now been considered, we learn that the action of light of every hue upon the retina is not unitary but dual in its nature, one part consisting of a direct effect and the other of a reflex. The direct action affects the one sensation involved if the color is red, green, or violet, or the two sensations if orange, yellow, or blue. The reflex process affects all three sensations in every case. According to the three component theory of color vision it is generally held[24] that equal and simultaneous stimulation of the three primary sensations results in the perception of white. But even if the several stimulations need not be equal, no doubt a definite ratio of excitations is involved in the white process.

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[24] Abney: Researches, p. 231.

When, for example, red light falls upon the retina, the sensatory or sensory reflex excites the three fundamental sensations sufficiently to cause the perception of white; the direct action of red affects only the corresponding sensation, resulting in the simultaneous perception of red. What appears finally to consciousness therefore is the red color overlying, as it were, a substratum of white of an intensity depending on the strength of the original red stimulus. The same reasoning applies to all color impressions, except that in the case of compound colors, two sensations are directly involved. If the color excitations are very intense, the sensation of white may be so powerful as to render the direct effect of the color almost vanishingly small. Hence all colors when of great intensity would approximate whiteness in appearance.

While this view seems to be completely in harmony with the experimental evidence, yet color perception may be expressed in other terms which offer some advantages. Every color affects part of the receptors directly and the remainder in the same retinal area reflexly. These in every case, include the whole of the colors of the spectrum which when combined become white light. Hence the two portions of the color process, the direct and the reflex, occupy qualitatively a complementary relationship. When any sensation is affected directly and fatigued, with a consequent diminution of the brightness of the color stimulus, the luminous response of the remainder is enhanced. These two effects are not usually quantitively capable of exactly balancing each other and so producing white. At moderate intensities the whole of the reflex effect will unite with some proportion of the direct and produce white, the residuum being the color. From these considerations color perception may be brought under Sherrington's Principle of Reciprocal Innervation, if that Principle may be enlarged to include sensations within its scope.

The white light underlying all color perception has been widely recognized. In Hering's theory,[25] a separate visual process is assigned to the white-black sensation. In Wundt's theory, it is assumed that "two different stimulation processes are set in action by every retinal excitation, a chromatic and an achromatic. Both stimulations follow different laws with increasing stimulus intensities. At low intensities the achromatic surpasses the chromatic; at moderate intensities the chromatic is the relatively stronger; at the highest intensities the achromatic regains superiority."

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[25] For valuable expositions of the chief modern theories see "Colour Vision," by J. H. Parsons.

Mrs. Ladd-Franklin assumes that "in the earliest stages of its development the visual sense consisted of grey." Out of this achromatic sensation the color sensations developed by a process of molecular differentiation.

McDougall provides an independent white process in addition to the three fundamental sensations, red, green and violet. From his numerous researches, Abney[26] concluded that "it appears as if light were the fundamental sensation caused by the main vibration generally, whilst color is, as it were, an overtone to which the receiving nerves are less susceptible than to light, the further away they are situated from the centre, and may be due to the form of vibration."

In some of his later work Abney[27] also inclined to the view that he had possibly separated the white from the color sensations. But according to the experimental evidence adduced in this paper, such a separation is impossible with the direct action of light.

Parsons[28] also states: "But we are confronted with another fact, less easy of explanation, viz., that great increase of intensity of the light not only alters the hue, but also alters the saturation, so that eventually it produces only the sensation of white light. It would seem therefore that luminosity is in some recondite sense an inherent "whiteness" in the color itself, differing in degree in different spectral colors, and varying with the intensity of those colors. Clearly we are here, at the outset, face to face with a physiological fact of immense importance, and much of the difficulty of color vision is concerned with this fact."

But not alone are intense color sensations achromatic. The same phenomenon reappears when the intensity of colors falls very low. So important has this peculiarity been deemed that a special theory for its explanation has been formulated by von Kries,[29] called the Duplicity Theory, which has received wide acceptance. This theory recognizes the existence of two kinds of vision, the photopic, which is chromatic, and the scotopic, or vision at very low intensities, which is achromatic. Two different mechanisms, the cones and rods respectively, are assumed to be involved in producing these very different types of vision.

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[26] Phil. Trans. A., *190*, p. 195; 1897.

[27] Phil. Trans. A., *205*, p. 348.

[28] "Colour Vision"; p. 29.

[29] Parsons: "Colour Vision," p. 203.

But is such a theory necessary? All effects concerning chromatic and achromatic vision seem susceptible of explanation by assuming that at high intensities all colors excite balancing reflexes of equal magnitude which combine to produce white. As the intensities of the colors become smaller, the intensities of the reflexes also diminish, but at a more rapid rate, leaving a greater or less unbalanced residuum of color, which is that normally perceived. Finally, as the intensities of colors are further reduced the reflex sensations again become equal in magnitude with resulting achromatic vision. The whiteness which is always present appears to consciousness usually as a modification of the saturation of color. At medium intensities, color predominates over whiteness; at extremes, both high and low, whiteness equals or predominates over color. Other peculiarities of vision such as night-blindness, may render the duplicity theory desirable or even necessary; but it seems quite superfluous in connection with the very phenomena which it was chiefly designed to explain.

There is universal recognition that spectral colors are far from being saturated. This has found expression by color theorists generally; and it has been specifically stated by Helmholtz, Hering, König, and Exner, for example, that the colors they selected as primary were all to be regarded as more saturated than their spectral values.

Reasons have been given why a color cannot be seen directly apart from its underlying white. Saturation is at once desired and impossible to secure. Increasing or decreasing the intensity of stimulation too far results in lessening the saturation still further. While direct action apart from reflex cannot in its very nature be obtained, the reflex may exist apart from the direct in the form of after images, when the direct action of light has ceased. In this connection, certain observations by McDougall are of remarkable interest and importance, and are in full agreement with the principle of reflex color sensations. According to MacDougall,[30] "An important feature of the after-images of bright white light is that, after a first short period in which two colors fuse to give yellow, or, as is the case after the brightest lights, all three fuse to give white, the colors that in turn occupy the area of the after image, alone and unchanging for considerable periods, are red, green, and blue only, and these are in every case of exactly the same color-tone, although varying in brightness in different cases and in different stages of one after-image. The red is a rich, crimson red, decidedly less orange than the red of the solar spectrum, the blue is a rich ultramarine, and the green a pure green, having no inclination towards blue or yellow...... They are the purest, richest, most saturated colors that I have ever experienced, and I believe that in this way, and this way only, one may experience absolutely simple, i.e. unmixed and fully saturated color sensations."

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[30] Quoted from McDougall by Parsons: Color Vision, p. 111.

It would scarcely be possible to imagine experimental evidence more in harmony with the principle of reflex color sensations than these observations of McDougall.

There seems no reason to doubt that simultaneous contrast can be brought under the operation of this principle. "For the most important element in color contrast is the opponent or complementary effect,"[31] which is precisely what the principle of reflex sensations would lead one to expect. The fact that the phenomenon is reciprocal as well as complementary, is also in harmony with this principle. Indeed, binocular contrast is explained by the curves presented above. For example, if red light falls on the right eye and green on the left, two effects are produced on each retina. The red light causes fatigue of the red and enhancement of the green and violet on the right retina. The effect of green on the left retina is transferred to the right in the form of a reflex enhancement of all three sensations. Some modification of the appearance of the red is bound to occur, which is connected with its complementary. Similarly in the left eye, the appearance of the green color is modified by the reflex influence of red. The combined reflex and fatigue curves therefore prove that contrast effects must occur, and prove also that their mutual influences are in complementary directions.

Since the equilibrium colors do not change the normal curves, it seems probable that pairs of these colors should not produce any contrast effects, either binocular or monocular. The equilibrium colors $.660\mu$ and $.570\mu$, for example, should not modify each other's appearance in the least. Indeed, this method might be used to verify the equilibrium points.

The familiar experiment on successive contrast also has new light thrown upon it by the principle of reflex stimulation of the color sensations. If a patch of red color is intently observed for twenty or thirty seconds and then a white surface is looked at, a patch of green of the same shape as the original red is seen. The explanation usually given is that the red receptors are fatigued by the red light, while those for the other sensations are either less or not at all affected. Consequently the white light excites the green and violet receptors much more than the red.

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[31] Parsons; loc. cit., p. 128.

This explanation must now be modified by remembering that while the red sensation is being fatigued, the remainder are being reflexly enhanced. This great enhancement of the green sensation and to a less extent of the violet, is responsible for part and probably the major part, of the observed complementary effect.

The explanation of complementary colors is very direct. Two colors are complementary when their combined direct and reflex effects result in equal stimulation of the three fundamental sensations, or in such proportionate stimulations as fuse together to produce white.

In his consideration of the Young-Helmholtz theory, Parsons[32] has briefly summarized some criticisms as follows:—"The greatest difficulty, however, is experienced in explaining the facts of induction. In general terms it is not difficult to conceive a diminution in response of the components in one direction, associated with an increase in another, after previous stimulation. We might thus account for the increased response to the complementary after stimulation with a given light. Indeed, such a view falls in well with other physiological findings, so admirably elaborated in Sherrington's work. If all spectral lights act upon all three components, then the increased response to the complementary after previous stimulation with a color can be explained, and this was the view adopted by von Helmholtz. It lands us, however, on the horns of a dilemma, for the facts of dichromatic vision —and the same is true of trichromatic—show that lights of greater wave length than about $.550\mu$ do not act at all upon the violet component, since no standard blue has to be mixed with the standard red to match colors in this part of the spectrum. Yet the saturation of yellow ($.589\mu$) is undoubtedly increased by previous stimulation with the complementary blue. Von Kries has shown that this effect is not to be explained by any alteration of the intrinsic light of the eye, but is caused by a quantitative change in the response to the secondary light. If yellow light acts only on the red and green components, we cannot explain on the theory the increase in saturation which follows previous activity in the blue components. Hess refuses to admit that the facts can be brought into line with the theory. We must therefore accept the theory as explaining satisfactorily *either* the phenomena of after-images *or* those of dichromatic vision, but not both. The large mass of accurate evidence which has now accumulated chiefly from the observations of Abney and von Kries and their fellow-workers, showing that all spectral lights do not act upon all the components makes it impossible to accept the explanation as it stands for successive induction. Moreover, successive induction is a complex condition allied to simultaneous induction, and it must be admitted that the facts of simultaneous contrast cannot be explained directly by the trichromatic theory alone."

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[32] loc. cit. p. 218.

The experimental results presented in this paper give a very exact and comprehensive answer to these criticisms. It has been found by experiment and abundantly shown in the above curves, that a diminution of response of the components in one direction is always associated with an increase in another, unless interfered with by darkness adaptation, and in a perfectly systematic manner. The assumption of Helmholtz that all spectral lights act upon all three components is found to be experimentally verified, though the connection is not by the direct action, as doubtless was Helmholtz's view, but by the reflex influence of light. It is found also that light of every wave-length, including that between $.550\mu$ and $.740\mu$ has an undoubted effect on the violet. The general failure to detect this is probably due to the neutralizing action of darkness adaptation.

Yellow light acts not only on the red and green components, but as the curves show, on the violet component as well. Attention has been directed also to the great reflex effect on the green-yellow which results from the action of the violet, as well as blue. This accounts adequately for the increase in the saturation of yellow by previous stimulation with the complementary blue.

The accuracy of the observations of the investigators mentioned in the above quotation need not be questioned. But their conclusion that all spectral lights do not act upon all components is conclusively negatived by the present experimental results. Possibly the method used by the author possesses somewhat greater delicacy than theirs, or more probably the transferable effects of darkness adaptation from one eye to the other may have concealed these phenomena from them just as it did from the author for some years.

Finally, in a manner similar to the explanation of binocular contrast, it is quite probable that the facts of simultaneous induction or contrast can be explained by the trichromatic theory when enlarged by the inclusion of the principle of reflex visual sensations.

The results of the experiments in this investigation are strongly opposed to the conclusions of Burch,[33] concurred in by Edridge-Green,[34] to the effect that "fatigue of the eye for any one color does not increase its sensitiveness for any other color." Edridge-Green further says that "if the eye be fatigued for yellow the blue of the spectrum is considerably diminished, not increased," and suggests that the effect is probably due to luminosity contrast.

If, however, the experiments of the latter were performed in a dark room, the large effect of darkness adaptation of the non-observing eye on the other will considerably overbalance the enhancement of the blue due to the reflex effect of the yellow. Since the coincidence point of the normal and other curves occurs at the junction of green and blue in the spectrum, no enhancement of this region takes place and therefore the effect of darkness adaptation is unopposed. Whatever hue of blue is selected, the observation of Edridge-Green is explained without introducing any other principle.

The reflex effects of color are of such magnitude in enhancing the visual sensations that it seems probable some method of seeing the reflex colors could be devised. While considering this question during the progress of the investigation it occurred to the author that some experiments described by Bidwell might be what were sought for.

The result of the sensory visual reflexes is, as we have seen, to reduce the saturation of colors by the production of white. But the impact of light on the retina arouses the reflex only after an interval of time which must be very short, as it is rarely noticeable. It follows therefore that colors falling on the retina should first be perceived for a very short interval of time much more saturated and brighter than in normal vision. Now Bidwell[35] states that "immediately upon the impact of the light there is experienced a sensation of luminosity, the intensity of which increases for about one-sixtieth of a second; much more rapidly towards the end of that period than at first. Then ensues a sudden reaction lasting also for about one-sixtieth of a second in virtue of which, the retina becomes partially insensible to renewed or continuous luminous impressions. The stage of fluctuation is succeeded by a sensation of steady luminosity, the intensity of which is, however, considerably below the mean of that experienced during the first one-sixtieth of a second."

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[33] Phil. Trans. B. p. 5; 1899.

[34] Physiology of Vision, p. 235.

[35] Proc. Roy. Soc., *56*, p. 132; 1894.

These observations are quite in harmony with the principle of reflex sensations.

Further, Bidwell[36] describes an experiment as follows: From a disk a sector of 45° was removed. One half of the remainder was covered with black velvet and the other with unglazed grey or buff paper. A red or other colored card is placed back of the disk in such a position that it can be seen through the open sector. The disk and card are well illuminated with white light. When the disk rotates from 6 to 8 times per second the red ceases to be visible, and in its place is seen the complementary color.

The explanation given by Bidwell and concurred in by Abney[37] is that the brief flash of red light fatigues the red receptors which thereby respond much more feebly than the green sensation when the white light reflected from that part of the disk in its turn reaches the eye; or that the effect is due to successive contrast after an exceedingly brief stimulus.

From the standpoint of this paper, the explanation is altogether different. The initial impulse of direct light, much brighter than normal, arouses the reflex sensations in the brief interval of its duration, from 0.02 to 0.015 second, and is then cut off, allowing the complementary portion of the reflex sensations, which ordinarily is overpowered by the continuous red light, to become visible. Since the eye must always be under some influence, whether of light or darkness, the continuance of either of which alone is fatal to the visibility of the effect, the retina must be maintained in a state of sensitive equilibrium by applying the two opposing effects, light and darkness, alternately. For, according to Bidwell, the brief application of light enhances the brightness, and we have shown that darkness always diminishes the brightness of colors. This explanation does not involve fatigue in the least. Negative after images are the various reflexes dying out in unequal times; the Bidwell effect is the reflex sensation in its beginning.

If this explanation of the phenomenon is correct, we can bring under the principle of reflex sensations, the hitherto curious and fleeting color effects and recurrent images in the other disk phenomena of Bidwell, as well as in those of Sherrington, Benham and others.

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[36] Proc. Roy. Soc., *61*, p. 269; 1896.

[37] "Researches in Colour Vision," p. 396.

Edridge-Green[38] has recently published some observations which may with advantage receive brief consideration. He formed a white with a mixture of certain red, green, and violet colors. After fatigue with red of wave length .670μ the white light was viewed and found to be green in appearance. By reducing the green component to half its original amount, whiteness was restored. No change in the original white was seen when the eye was fatigued with red of wave length, .780μ. This effect is interpreted by Edridge-Green as opposed to the three-component theory of color vision. On referring to the reflex curves for red, Fig. 6, it will be found that the color .670μ produces a fairly large reflex in the green. Fatiguing with this color therefore not only diminishes the intensity of the red but enhances the brightness of the green to such an extent that a smaller portion is sufficient to reestablish the balance and so restore whiteness. The reflex obtained for .740μ is very small, and as the figure shows, the longer wavelengths show diminishing reflexes. Therefore the reflex enhancement of the green from fatigue with .780μ will scarcely be noticed. No appreciable disturbance of the white equation will probably result.

Edridge-Green further states that when the eye is fatigued with the color .760μ and the red .670μ is viewed, it appears yellow or greenish-yellow, which, he states, could not be the case if the red sensation only had been affected.

In explanation of this effect, it may again be stated that the color .740μ produces a distinct reflex in the green-yellow region, and it is probable that .760μ will also have an appreciable effect. As no doubt all colors produce reflex effects of varying magnitude, the change of color observed is explained.

From Fig. 6 it seems probable that the Edridge-Green white equation will not be affected by fatiguing the eye with the equilibrium color .660μ, and that the disturbance of the balance of colors will increase to a maximum with a fatiguing stimulus of .687μ, and thence fall off to become inappreciable with the last part of the red at .780μ.

The observations of Edridge-Green appear to fall in quite naturally with the experimental results herein presented, and seem to be in no sense opposed to the three-component theory coupled with reflex sensations.

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[38] Nature, *107*, p. 826; 1921. Also Proc. Roy. Soc. B, *92*, p. 232; 1921.

The production by all colors of a reflex enhancement of the green-yellow part of the spectrum, no doubt accounts for the commonly observed fact that colors when diluted with white light tend towards yellow.

Since it is only the direct effects of color that have received such extensive investigation, it is not surprising that scores of color theories have been formulated. Probably most theories have in them some element of truth. But a solution of the "enigma of color vision" is not possible unless the whole effect of light waves on the complicated visual apparatus is known. The reflex sensations have never been taken account of, as hitherto their existence has only been suspected. To some extent one theory must be excepted from this statement. With such fragmentary facts as were known largely through the observations of McDougall himself, that investigator elaborated a theory[39] which, in a measure, recognizes the existence and function of reflex effects. He adopted the three-component theory, but adds, what from the standpoint of the present paper is unnecessary, a white sensation.

No theory at present formulated is sufficiently fundamental to include all the phenomena. But if the theory of three components, to which the names of Young and Helmholtz are attached, is enlarged by the inclusion of the reflex effects elucidated to some extent in this paper, that theory already so strongly grounded will afford explanations of and draw to its support many facts which have hitherto been unexplained, or even used against it. This statement must be qualified in one respect. Violet must be regarded as one of the fundamental color sensations in addition to red and green. For if these results speak with any decision at all, it is that blue as well as yellow are compound sensations.

The idea that the color sensations have developed out of a primitive white process receives no support from these experiments. There is no apparent development in any one direction more than in any other. But if there were development, it would rather be that white had been added to color and not color to white.

On referring to the reduced curves in Figs. 18 and 31, it will be seen that several of the equilibrium colors show vestiges of the three reflex depressions. Since the sensation curves are three in number it would appear to follow that absolute equilibrium would only occur when all three intersected in one point, or that one was zero in value when the other two intersected. As these conditions are never completely realized, perfect equilibrium seems to be impossible. Should more delicate methods of study of the visual reflexes be devised, as will probably be the case, this imperfection of equilibrium may then be more apparent than is the case with the persistency curves.

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[39] Parsons, Loc. cit., p. 274.

It is interesting to note that Burch[40] found the mean value of the transition point between red and green, for seventy persons, to be $.573\mu$, and between green and blue to be $.5003\mu$. The former is nearly the equilibrium color $.570\mu$, and the latter is almost the mean of the group of three equilibrium colors, $.480\mu$, $.505\mu$, and $.520\mu$.

It is quite possible that the sensory visual reflexes may also account for the intrinsic light of the eye. This is a general sensation on the retina of "very dark greyness." "That endogenous stimuli are the cause can scarcely be doubted, but whether these are primarily retinal or of central nervous origin remains uncertain, though it is now generally agreed that they are central."[41] Since the three sensations are always together affected reflexly the result will always be the production of white light of some intensity. This colorless light would necessarily be of central origin.

The determination of the reflex sensations of the color-blind will no doubt give valuable information concerning the nature of this peculiarity of vision. In a former research,[42] the author obtained the normal curves of about twenty-four subjects, including one totally color-blind, which were readily classified into six of the seven possible types of color blindness according to the Young-Helmholtz theory. These now need to be supplemented with the reflex and fatigue curves of similar types.

It is possible that the reflex effects in the color-blind, due to one or two or even all three sensations may be of equal magnitude with the direct effects and so produce white or grey in place of one or more of the color sensations. In total color blindness, vision may be achromatic because of constant equality between direct and reflex effects at all intensities, a condition which may also exist at moderate intensities in the peripheral retina in normal eyes. One fact only may be adduced at present. The explanation of the neutral point of the color blind may be the same as for complementary colors in normal eyes,—equality of direct and reflex sensations of *two* colors. The average position of the neutral points determined by seventeen color blind subjects was .509μ, of which the greatest was .516μ and the least .495μ. This mean value lies between the two equilibrium points .505μ and .520μ, and is almost identical with one of the coincidence points, .501μ, of the fatigue and reflex curves.

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[40] Parsons: Colour Vision, p. 115.

[41] Ibid: p. 104.

[42] Phys. Rev., *15*, p. 193; 1902.

V. Evidence for Sensory Reflex

The author is not a physiologist and by no means holds the attitude perhaps implied by the brief, dogmatic title of this communication. It is obvious that physiology must decide whether these phenomena may properly be included under sensatory or sensory as distinguished from motor and secretory reflexes.

In support of this view, however, the following considerations are suggested.

The optic nerve of each eye proceeds to the optic chiasma where the decussation of the fibres from the nasal side of each retina takes place. From the optic chiasma, each optic tract proceeds backwards and ends in the lower visual centres on the corresponding side. From these centres, the corresponding radiations proceed to the occipital cortex of the cerebrum where the higher visual centres are situated. This constitutes the course of the afferent fibres from each retina to the occipital cortex.[43]

Arising from the cells of the occipital cortex are efferent[44] fibres which proceed via the optic radiations to end in the lower visual centres. From these centres new efferent fibres arise which travel to each retina.

The presence of both afferent and efferent fibres in conjunction with the retina of each eye, establishes the anatomical basis for the conduction of impulses from and to each retina. Up to the present no phenomenon has been observed which would demand the existence of efferent fibres to the retina from the higher centres. The fact, as is shown in this paper, that a color stimulus upon one retina enhances the perception of colors in the other retina indicates that there must be some route whereby the two eyes mutually affect each other to produce opposite effects. Due to the existence of the anatomical essentials of a reflex arc, i.e., the afferent and efferent fibres connected with each retina, it is possible to explain the effect observed by a reflex occurring which in some way changes the state of the receptor elements of these organs in the unstimulated retina. It is to be noted in the foregoing that the reflex observed from retina to retina is not of the same essential nature as the conventional motor or glandular reflexes, since in the first, the efferent impulses do not produce a motor or a secretory effect, but in some way alter the visual end organs so that they perceive certain colors in a different way. For this reason it seemed appropriate to call the new effect a sensatory or sensory reflex. This effect is not only transferred from one eye to the other but occurs also in the directly stimulated retina as well.

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[43] Text-Book of Anatomy. Cunningham, 5th Ed. pp. 620 and 709.

[44] Cunningham, loc. cit., p. 620. Also Gray, Anatomy, p. 830. (1920 ed.).

The experimental results set forth in this paper seem to be included in Howell's[45] definition of a reflex action, which is stated to mean "the involuntary production of activity in some peripheral tissue in consequence of a stimulation of afferent nerve fibres," the conversion of the afferent into the efferent impulse being effected in the nerve centres.

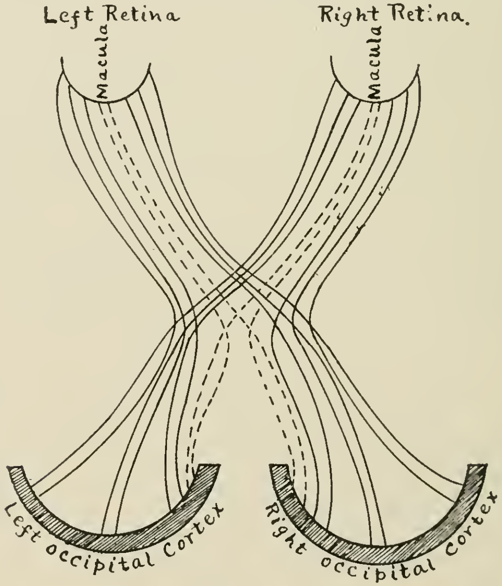

FIG. 35. *Optic Tracts.* (*Schaefer.*)

In Fig. 35, is reproduced Schaefer's very general sketch of the nervous tracts of the eye. In Starling's treatise on Human Physiology,[46] from which this figure is taken, Hartridge briefly describes the functions of the four classes of nerve fibres connected with the retina.

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[45] Text-Book of Physiology, 8th Ed., p. 139.

[46] 3rd Ed., p. 552.

With three of these we are not at present concerned. But the fourth class is thus described: "The function of these inter-retinal fibres is not known definitely. It has been suggested that they cause changes in one retina when light falls on the other, as for example, cone movement . . . lastly binocular contrast and after images have been ascribed to them."

Hartridge does not describe the structure of these fibres sufficiently in detail to enable one to decide whether they are of such a nature as to constitute the reflex arc. But the proof that binocular contrast is due to the reflex color process, as shown above, may justify the ascription of this phenomenon to the fibres in question.

The possibility of the existence of a sensory reflex led Sherrington[47] to make extensive experimental search for it in the sensation of vision.

In further support of this view, that the effects observed are of a reflex nature, it is interesting to note that the latent period of this reflex, i.e., the time taken for the causative impulse upon the retina to produce its initial reflex effect, compares favourably with the latent periods of well known motor reflexes.

If it is assumed that the Bidwell effect previously described is due to a sensory reflex process, then from his description of the experiment, the appearance of the complementary color occurs in from about 0.015 to 0.02 second, which is the latent period.

The times which Jolly[48] obtained in estimating the latent period of the motor reflex known as the 'knee-jerk' in three cats are 0.0053 sec., 0.011 sec., and 0.012 sec. In these animals the spinal cord was severed so that the reflexes were free from cortical control, a condition which invariably decreases the latent period of a reflex. The order of magnitude of the periods of the sensory and motor reflexes is the same. From the arrangement of both afferent and efferent fibres it may be concluded that the sensory reflex is under the control of the higher centres, and therefore there is a legitimate reason for its period being somewhat longer than those measured by Jolly.

It may also be pointed out that the 'knee-jerk' is the most rapid reflex known,[49] and when it is found that the latent period for the sensory reflex compares favourably with that of the most rapid motor reflex there seems little doubt as to its nature.

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[47] Integrative Action of the Nervous System. Lecture X, p. 354.

[48] Starling: loc. cit. p. 335.

For other reflex time determinations see Howell, loc. cit. p. 145.

[49] Starling: loc. cit. p. 335.

My colleague, Dr. C. H. O'Donoghue, Professor of Zoology, who very kindly read this last section, suggested that possibly the 'sensory reflex' may excite a secretory action connected with the production of the visual purple or other visual substances. This may be decided by ascertaining whether secretory action is sufficiently rapid to perform its function in the brief time limit allowable.[50]

If, however, the visual purple is to be regarded as a factor in reflex visual phenomena, another function will have been added to the list already suggested for this puzzling substance.

I desire to record my appreciation of the kindness of Messrs. A. Hollenberg, B.A., and M. S. Hollenberg, M.A., in bringing to my attention anatomical and physiological considerations intimately concerned with the experimental results of this enquiry, and to Mr. W. A. Anderson, B. Sc., for assistance in reducing the measurements.

I am especially grateful to the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, for a substantial grant in aid of my researches in color vision.

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0 See Starling loc. cit. p.711

June 1929

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ON THE EFFECT OF AURAL FATIGUE UPON THE CRITICAL FREQUENCY OF PULSATION OF TONES.

On the Effect of Aural Fatigue upon the Critical Frequency of Pulsation of Tones.

By Mollie Weinberg, *M.A., M.Sc., Research Student of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, and* Frank Allen, *Ph D., F.R.S.C., Professor of Physics, University of Manitoba*[*].

THIS investigation is concerned with the effects of fatigue upon the persistence of audition, or the duration of the tone at the critical frequency of pulsation or flutter. The results herein described seem to throw new light upon some of the phenomena of acoustics, and also upon the probable structure of the aural mechanism by means of which tones are perceived and differentiated from each other.

The apparatus used is the same as that described in a previous communication[†].

The source of sound was a tonvariator blown by a stream of air from a constant-pressure tank. The tonvariator was enclosed in a sound-proof box having one opening through which the sound could escape. The periodic interruption of the continuous sound was effected by the rotation of an aluminium disk in which were four holes of the same size as that of the opening in the box. For measuring the time of rotation of the disk, a speed counter and a clock beating half-seconds were electrically connected to a chronograph. When making measurements, the speed of the disk was adjusted so that the pulsation or flutter of the sound became just imperceptible, and then recorded. For fatiguing the ear, another tonvariator similar in all respects to the one in the sound-proof box, was used. Both instruments were calibrated from Standard Tuning Forks.

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[*] Read at the meeting of the Royal Society of Canada, Ottawa, May 1922.

[†] "On the Critical Frequency of Pulsation of Tones," *supra*, p. 50.

An attempt was made to determine the progessive effect of fatigue for increasing intervals of time, but the results were too uncertain to be of much use. The maximum fatigue seemed, however, to be attained in about two minutes for low intensities of sound. In the following experiments this interval of time was therefore allowed for fatiguing the ear before each measurement was made.

Two methods were used in this part of the work, one the converse of the other, in the hope that the results obtained from one would confirm those obtained from the other. Such happily appeared to be the case.

The first method consisted in fatiguing the ear with a tone of constant frequency, and taking measurements on tones varying over a range of about fifteen vibrations above and the same number below the fatiguing tone. The second method consisted in taking measurements on a tone of constant frequency, and varying the fatiguing stimulus over a similar range of about thirty vibrations.

In making measurements the following procedure was adopted. At a definite blowing-pressure, the tonvariator in the box, upon which the measurements were made, was adjusted to give a tone of any desired pitch, and the second tonvariator was accurately tuned with it by means of eliminating beats. The left ear was then fatigued with this tone for two minutes by holding it close to the orifice of the tonvariator, and immediately afterwards the measurement of the critical frequency of pulsation or flutter of tone was made. The fatiguing process was again and again repeated, and similar measurements were made on a selected series of tones.

Sets of such measurements are given in Table I. The persistency curves defined by these points were taken to represent the effect produced by fatiguing the ear with tones of constant frequency. The curves are shown in fig. 1. The curve through the small circles is the normal obtained with the unfatigued ear, and is plotted from the data in Table VI., F, which is taken from a former communication *. The broken line curves through the × 's are the fatigue curves. These are characterized by prominent elevations covering in each case a range of about sixteen vibrations, with the maximum occurring at the frequency of the fatiguing tone, as is to be expected.

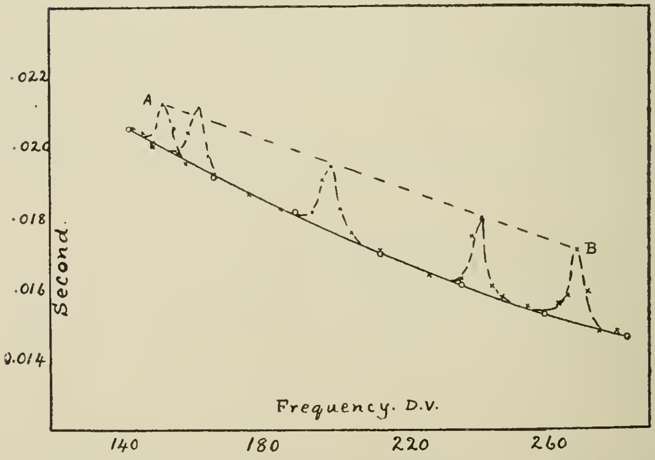
* "On the Critical Frequency of Pulsation of Tones," *supra*, p. 50.

TABLE I.

Fatigue Curves for different Frequencies at same Pressure.

Pressure. P.	Frequency. N.	Duration. D.
	Normal Curve.	
	D.V.	Sec.
1·82 cm.	143·0	0·0206
„	167·0	·0192
„	190·0	·0187
„	214·0	·0170
„	237·0	·0161
„	260·5	·0153
„	284·0	·0146
	Fatigue Curves.	
1·82 cm.	133·0	0·0206
„	146·0	·0205
„	149·5	·0202
„	152·5	·0213
„	155·5	·0206
„	158·2	·0196
„	167·0	·0193
1·82 cm.	227·8	0·0164
„	237·0	·0163
„	240·0	·0175
„	242·8	·0180
„	245·5	·0161
„	248·2	·0158
„	255·8	·0155
	Fatigue Curves (*cont.*).	
	D.V.	Sec.
1·82 cm.	149·0	0·0201
„	156·4	·0199
„	159·2	·0205
„	162·2	·0212
„	165·0	·0198
„	168·0	·0192
„	176·5	·0187
1·82 cm.	185·8	0·0183
„	194·5	·0182
„	197·2	·0191
„	200·0	·0195
„	202·8	·0183
„	205·6	·0176
„	213·8	·0171
1·82 cm.	255·8	0·0155
„	264·0	·0156
„	267·0	·0158
„	269·6	·0171
„	272·4	·0159
„	275·2	·0148
„	281·0	·0148

Fgi . 1.



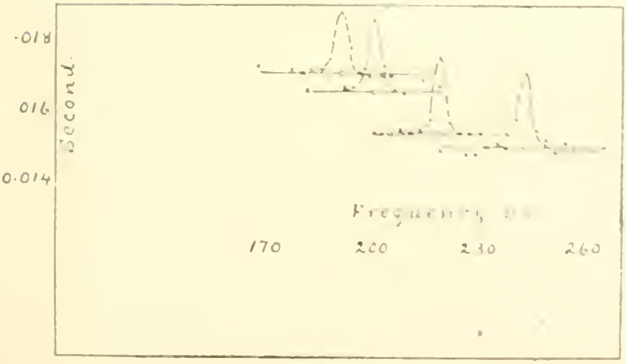
By the converse method, similar fatigue curves were obtained, the measurements being made, in each case, on a constant tone, and the fatiguing tone being varied over a range of about forty vibrations, as shown in Table II. These fatigue curves are plotted in fig. 2. The elevations in these

TABLE II.

Fatigue Curves—by Second Method (Constant Pressure).

P.	N.	D.	P.	N'.	D.
		Sec.			Sec.
	Normal Point.			Normal Point.	
1·78 cm.	190·5	0·0171	1·78 cm.	218·0	0·0154
	Fatigue Curve.			Fatigue Curve.	
1·78 cm.	167·0	0·0173	1·78 cm.	206·0	0·0154
	176·6	·0172		207·1	·0155
"	179·3	·0171	"	210·0	·0154
"	182·0	·0172	"	212·7	·0156
"	185·0	·0172	"	215·7	·0158
"	187·5	·0175	"	218·4	·0175
"	191·5	·0188	"	221·5	·0157
"	193·2	·0178	"	224·0	·0154
"	196·0	·0171	"	226·6	·0154
"	198·5	·0170	"	229·8	·0154
"	201·7	·0170		237·1	·0154
"	204·5	·0170			
"	213·6	·0169			
	Normal Point.			Normal Point.	
1·78 cm.	199·8	0·0166	1·78 cm.	211·8	0·0150
	Fatigue Curve.			Fatigue Curve.	
1·78 cm.	181·0	0·0166	1·78 cm.	218·4	0·0149
"	192·2	·0167		226·0	·0148
"	194·0	·0167	"	228·7	·0148
"	196·9	·0172		231·6	·0150
"	199·8	·0186		234·5	·0151
"	202·6	·0173	"	237·0	·0150
"	205·3	·0166	"	240·0	·0157
	208·1	·0165	"	242·8	·0171
	218·4	·0167	"	245·5	·0155
			"	248·2	·0152
				251·0	·0149
			"	254·0	·0151
			"	256·8	·0149
			"	265·0	·0150

Fig. 2.



curves are symmetrical with the axis of frequencies, since the normal has only one value, which is the duration of the tone on which measurements were made at the critical frequency of pulsation. This is indicated in each case by a small circle at the proper frequency, through which the full horizontal line is drawn. The elevations again are found to cover the same range of about sixteen vibrations.

In the tables, P is the blowing pressure, in centimetres of water, to which the intensity of the sound of the tonvariator is proportional*; N is the frequency of vibration of the tonvariator; and D is the duration of the tone at the critical frequency of pulsation, or flutter.

The curves indicate that as a result of fatigue the persistency of sound impressions is greatly increased. This increase is a maximum when the frequency of the fatiguing tone is the same as that upon which measurements are taken, and diminishes very rapidly as the interval from the frequency of the fatiguing tone is increased. The entire range affected is about sixteen vibrations, or about eight on each side of the maximum. The steepness of the slope indicates that only a few vibrations very near the maximum on both sides are affected to any great extent.

The general nature of the fatigue curve is seen to be the same for each frequency. It will be noticed, especially in fig. 1, that as the frequency is increased the height of the elevation also increases. So perfectly do they vary together, that in this figure the maxima of the elevations lie on a straight line, shown in the figure as the broken line AB. No doubt if the ear were exposed to sounds of considerable intensity for a couple of minutes while instrumental adjustments were being made, the apparently "normal" curve thereby obtained would in reality be the straight line forming the locus of the maxima of the fatigue elevations. Possibly this may have been the case in Mayer's experiments, and may explain why his normal curves were straight lines, as indicated in a former communication †.

The elevations also show a slight gradual widening of their bases as the frequency is increased. This would indicate that the range of resonance arches in the ear affected by any tone is slightly greater as the frequency is raised. The range of frequencies used in this investigation, consisting of but one octave, is, however, too small for any reliable conclusion to be drawn.

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* Misses Love and Dawson, Phys. Rev. vol. xiv. p. 49 (1919).

† "On the Critical Frequency of Pulsation of Tones," *supra*, p. 50.

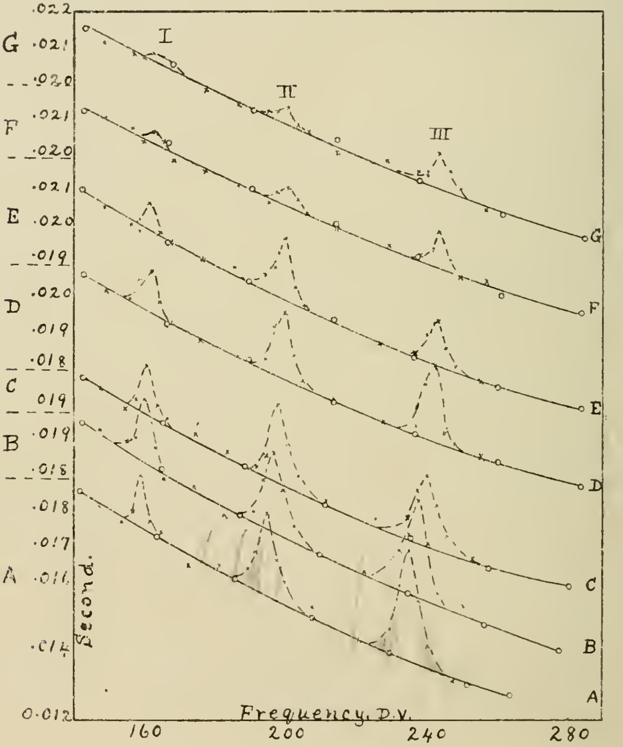
As indicated above, the elevations increase in height as the frequency of the fatiguing tone is increased. This may be caused by an increase in the sensitiveness of the resonating mechanism of the ear on account of pressure. In support of this idea an experiment due to Gellé may be cited. If a tuning-fork is pressed against the upper part of the forehead until its vibrations are faintly heard, and then a finger be pressed against the ear so as to increase the pressure on the membranes, the physiological intensity of the tone is greatly increased.

When the pitch of a tone is raised, the waves impinge upon the membranes of the ear with increasing frequency. The resonating arches may not therefore have sufficient time in which to recover from one impulse before the next wave arrives. The rising frequency of the tone may produce a certain steady increase of pressure, which, in turn, increases the sensitiveness of the auditory receptors. The resonating arches consequently are disproportionately fatigued and in such a condition respond more sluggishly to the stimulus, and the duration of the tone is increased when the frequency of pulsation reaches its critical value.

In fig. 3 are shown three (vertical) series of fatigue curves, each series representing the effect of fatigue of approximately the same frequency for seven different pressures or intensities. In series I. the fatiguing frequency was about 162, in series II. about 198, and in series III. about 240. The complete data are given in Table III. In examining this figure, it will be noticed that the lowest curve, A, is that for the lowest blowing-pressure, which gives the weakest tone, and the others represent tones gradually increasing in loudness. The curves are drawn to the same scale. The data for the normal curves are in Table VI. The columns N, in Table III., contain the tones upon which measurements were made.

The three series again show that the effect of fatigue is to increase the time of the critical frequency of pulsation. Also this increase becomes less as the intensity of the tone becomes greater. The diminutive size of the elevations in the curve G for the loudest tones employed indicates that for very intense sounds the fatigue elevations would disappear altogether. This might not be due, however, to the absence of fatigue, but to the probability that at higher intensities the ear is fatigued in much shorter time—that is, during the time in which the measurements of the critical frequency of pulsation were being made. In that case, what would appear to be a smooth normal curve would in reality be the line through the maxima of a series of fatigue elevations as pointed out above. In fig. 3 the summits of the fatigue elevations in the curves A, B, C, and D lie quite accurately on straight lines, and the remainder nearly so.

Fig. 3.



These curves are fully confirmed by others obtained by the second method—that is, by measuring the critical frequency of pulsation of a tone of constant frequency, the fatiguing tone being varied in pitch. The measurements are shown in Table IV. and the curves corresponding in fig. 4.

TABLE III.

Fatigue Curves. First Method.

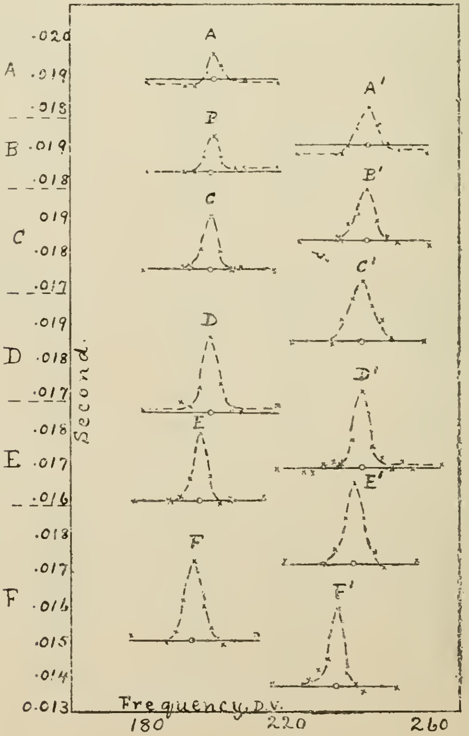
N.	D.	N.	D.	N.	D.
I G.		II G.		III G.	
Press., 2·40 cm.		Press., 2·40 cm.		Press., 2·40 cm.	
Fatiguing Tone, 163·0.		Fatiguing Tone, 201·0.		Fatiguing Tone, 244·0.	
149·0	0·0211 sec.	186·7	0·0194 sec.	229·0	0·0178 sec.
157·2	·0208	195·2	·0197	238·4	·0175
160·0	·0207	198·0	·0193	241·2	·0174
163·0	·0208	201·0	·0196	244·0	·0180
165·9	·0207	203·8	·0188	247·0	·0175
168·0	·0204	206·7	·0186	249·8	·0170
177·2	·0198	215·0	·0180	257·0	·0164
I F.		II F.		III F.	
Press., 2·20 cm.		Press., 2·20 cm.		Press., 2·20 cm.	
Fatiguing Tone, 163·0.		Fatiguing Tone, 201·0.		Fatiguing Tone, 244·0.	
149·0	0·0210 sec.	186·7	0·0191 sec.	229·0	0·0174 sec.
157·2	·0207	195·2	·0186	238·4	·0171
160·0	·0203	198·0	·0189	242·2	·0173
163·0	·0206	201·0	·0190	244·0	·0178
165·9	·0203	203·8	·0187	247·0	·0170
168·8	·0198	206·7	·0183	249·8	·0165
177·2	·0195	215·0	·0179	257·0	·0164
I E.		II E.		III E.	
Press., 1·98 cm.		Press., 1·98 cm.		Press., 1·98 cm.	
Fatiguing Tone, 162·2.		Fatiguing Tone, 200·0.		Fatiguing Tone, 242·8.	
149·0	0·0205 sec.	185·8	0·0178 sec.	227·8	0·0167 sec.
156·4	·0200	194·5	·0176	237·0	·0163
159·2	·0198	197·2	·0178	240·0	·0169
162·2	·0206	200·0	·0186	242·8	·0173
165·0	·0198	202·8	·0172	245·5	·0165
168·0	·0195	205·6	·0167	248·2	·0160
176·5	·0190	213·8	·0163	255·8	·0156
I D.		II D.		III D.	
Press., 1·82 cm.		Press., 1·82 cm.		Press., 1·82 cm.	
Fatiguing Tone, 162·2.		Fatiguing Tone, 200·0.		Fatiguing Tone, 242·8.	
149·0	0·0201 sec.	185·8	0·0185 sec.	227·8	0·0164 sec.
156·4	·0199	194·5	·0182	237·0	·0165
159·2	·0205	197·2	·0191	240·0	·0175
162·2	·0207	200·0	·0195	242·8	·0180
165·0	·0198	202·8	·0183	245·5	·0161
168·0	·0192	205·6	·0176	248·2	·0158
176·5	·0187	213·8	·0171	255·8	·0155
I C.		II C.		III C.	
Press., 1·53 cm.		Press., 1·53 cm.		Press., 1·53 cm.	
Fatiguing Tone, 161·0.		Fatiguing Tone, 198·0.		Fatiguing Tone, 240·3.	
147·5	0·0194 sec.	184·0	0·0176 sec.	225·8	0·0157 sec.
155·0	·0188	192·3	·0172	235·0	·0157
158·0	·0191	195·0	·0175	237·6	·0165
161·0	·0200	198·0	·0189	240·3	·0169
163·9	·0189	200·8	·0178	243·0	·0161
166·6	·0185	203·5	·0169	246·0	·0152
175·0	·0181	211·8	·0162	253·0	·0146

Table III. (*contd.*).

Fatigue Curves. First Method.

N.	D.	N.	D.	N.	D.
I B.		II B.		III B.	
Press., 1·45 cm.		Press., 1·45 cm.		Press., 1·45 cm.	
Fatiguing Tone, 160·8.		Fatiguing Tone, 197·0.		Fatiguing Tone, 238·0.	
147·3	0·0192 sec.	183·0	0·0168 sec.	222·8	0·0152 sec.
155·2	·0189	191·2	·0169	232·4	·0158
158·0	·0190	194·0	·0178	235·2	·0162
160·8	·0201	197·0	·0186	238·0	·0172
163·6	·0187	199·8	·0175	240·8	·0160
166·0	·0178	202·5	·0165	243·6	·0146
174·3	·0176	210·0	·0158	251·0	·0142
I A.		II A.		III A.	
Press., 1·25 cm.		Press., 1·25 cm.		Press., 1·25 cm.	
Fatiguing Tone, 159·4.		Fatiguing Tone, 195·0.		Fatiguing Tone, 235·2.	
147·0	0·0181 sec.	181·8	0·0164 sec.	221·2	0·0143 sec.
154·0	·0176	189·6	·0163	230·0	·0146
156·9	·0179	192·0	·0168	232·7	·0158
159·4	·0189	195·0	·0179	235·2	·0168
162·0	·0176	197·6	·0165	238·0	·0154
165·0	·0173	200·0	·0159	240·6	·0141
173·0	·0164	208·0	·0152	247·8	·0131

Fig. 4.



In Table IV. the tones in the columns, N'., were the fatiguing tones.

Table IV.

Fatigue Curves. Second Method.

A. Press., 2·40 cm. Constant Tone, 201·0. N'.	D.	A'. Press., 2·40 cm. Constant Tone, 244·0. N'.	D.
182·0	0·0188	224·5	0·0168
192·5	·0187	235·8	·0168
195·2	·0187	238·4	·0170
198·0	·0191	241·2	·0175
201·0	·0196	244·0	·0181
203·8	·0193	247·0	·0176
206·7	·0189	249·8	·0171
209·5	·0189	252·8	·0169
219·0	·0188	261·0	·0168

B. Press., 2·10 cm. Constant Tone, 201·0. N'.	D.	B'. Press., 2·10 cm. Constant Tone, 244·0. N'.	D.
182·0	0·0183	225·0	0·0163
192·5	·0183	236·0	·0164
195·2	·0183	238·4	·0168
198·0	·0187	241·2	·0171
201·0	·0193	244·0	·0178
203·0	·0187	247·0	·0169
206·7	·0184	249·8	·0164
209·5	·0184	252·5	·0163
219·0	·0184	261·5	·0162

C. Press., 1·98 cm. Constant Tone, 200·0. N'.	D.	C'. Press., 1·98 cm. Constant Tone, 242·8. N'.	D.
181·0	0·0175	223·0	0·0155
191·8	·0176	234·0	·0154
194·5	·0176	237·0	·0161
197·2	·0181	240·0	·0167
200·0	·0190	242·8	·0172
202·8	·0180	245·5	·0165
205·6	·0175	248·2	·0161
208·4	·0176	251·0	·0156
218·0	·0175	260·0	·0155

D. Press., 1·78 cm. Constant Tone, 199·8. N'.	D.	D'. Press., 1·78 cm. Constant Tone, 242·8. N'.	D.
181·0	0·0166	218·4	0·0149
191·2	·0168	226·0	·0148
194·0	·0167	228·7	·0148
196·9	·0172	231·6	·0150
199·8	·0186	234·5	·0151
202·6	·0173	237·0	·0151
205·3	·0166	240·0	·0157
208·4	·0165	242·8	·0171
218·4	·0167	245·5	·0155
		248·2	·0152
		251·0	·0149
		254·0	·0151
		256·8	·0149
		265·0	·0150

E. Press., 1·50 cm. Constant Tone, 197·0. N'.	D.	E'. Press., 1·70 cm. Constant Tone, 240·3. N'.	D.
178·0	0·0160	221·0	0·0143
188·2	·0160	232·0	·0142
191·2	·0161	235·0	·0146
194·0	·0166	237·6	·0155
197·0	·0179	240·3	·0165
199·8	·0167	243·0	·0155
202·5	·0159	246·0	·0145
205·2	·0160	248·5	·0141
215·0	·0161	258·0	·0143

F. Press., 1·16 cm. Constant Tone, 195·0. N'.	D.	F'. Press., 1·16 cm. Constant Tone, 235·2. N'.	D.
177·0	0·0152	217·0	0·0158
187·0	·0150	227·3	·0139
189·6	·0153	230·0	·0142
192·0	·0162	232·7	·0145
195·0	·0173	235·2	·0159
197·6	·0160	238·0	·0141
200·0	·0154	240·6	·0158
203·0	·0149	243·0	·0156
212·3	·0152	252·0	·0157

As in the preceeding figures, the height of the elevations shows that the persistence after fatigue becomes greater as the musical scale is ascended. The narrowness of the range of frequencies affected is seen more clearly in this figure because the reference curve or normal upon which the fatigue elevation is superimposed is the continuous horizontal line drawn through the normal value of the critical frequency of pulsation which is marked with a small circle.

In fig. 4, also, are shown two series of fatigue curves, each for a nearly constant frequency, but varying blowing-pressures or intensities. The lowest curves in the figure are for tones of weakest intensity. Again, the decrease in the apparent effect of fatigue as the tone increases in intensity is clearly indicated, as is also the increase in the effect of fatigue with increase of frequency—*i. e.*, the height of A′ is greater than that of A, of B′ than B, etc. The two methods therefore give results that are perfectly consistent with each other.

These results of aural fatigue are susceptible of explanation by assuming the existence of a resonance mechanism in the ear. We may suppose that the organ of Corti is that mechanism, the forty-five hundred arches acting as a series of resonators. For the sake of brevity, let us term those arches possessing natural vibration frequencies corresponding exactly to that of an entering wave the resonal arches of that frequency, and two or three adjacent arches on each side of the resonals the auxiliary arches. The evidence from the curves may be interpreted as follows. When a train of simple waves enters the cochlea, the resonal arches are set into vibrations of corresponding amplitude. The auxiliary arches are also quite strongly affected. Further, the arches corresponding to about five or six additional vibrations on each side of the resonals are also rhythmically disturbed, but the amount to which they are affected very rapidly diminishes as their distance from the resonals increases. If the ordinates of the fatigue elevation may be considered to represent the relative amplitudes of the vibrating arches, the intensities of the tones from the resonals and the auxiliary arches will be very great compared with those from the more distant arches, which will thereby become negligible. The mainly effective vibrations may therefore be considered to be those of the resonal and auxiliary arches.

But since the natural periods of vibrations of the auxiliary arches differ from each other as well as from the resonals, it would apparently follow that a single train of waves would produce perceptible tones of about five different frequencies. In the octave under study, these tones would differ from each other in the extreme by about the interval of a comma, 81/80, which is near the usual limit of perceptible difference in pitch. But the various arches vibrating in their natural periods would produce a series of beats which would be easily, as well as annoyingly, perceived.

This general objection, though urged by Watt* against the Helmholtz resonance theory, is removed by Helmholtz himself †. "An elastic body set into sympathetic vibrations by any tone vibrates sympathetically in the pitch number of the exciting tone; but as soon as the exciting tone ceases, it goes on sounding in the pitch number of its own proper tone. This fact, which is derived from theory, may be perfectly verified on tuning-forks by means of the vibration microscope."

This conclusion, applied to the present experimental results, indicates that the reason why the auxiliary arches are not heard in their natural frequencies is because they are constrained to vibrate with the same frequency as the resonals. As soon as the exciting tone ceases, the entire range affected also ceases to vibrate; the tones due to the natural frequencies of the auxiliaries are therefore not heard. The high degree of damping experienced by the vibrating arches immersed in the lymph of the cochlea quite naturally prevents any continuance of vibration after the exciting wave-train ceases to act.

The main objection of Watt to a resonance theory is that the arches on each side of the resonals do not give experiences in conformity with the law of specific energies of sense. Watt may have been justified in his criticism since, according to Helmholtz ‡ himself, the effect of an exciting tone was distinguishable on the resonating arches responding to a range of two whole equally-tempered tones; that is, in the octave we are considering, about sixty-four vibrations. Helmholtz's curve is reproduced in fig. 5 in comparison with the fatigue curve of the tone of frequency 242·8, the measurements of the critical frequency of pulsation being made on a series of tones ranging from 218·1 to 265 vibrations, and the blowing-pressure being 1·78 cm. The data for the fatigue curve are given in Table V. The resonating arches disturbed, according to Helmholtz's curve, extend over a range more than four times as great as that indicated by the fatigue experiment. In estimating the data for his curve, Helmholtz states that exactness is out of the question. The method of the critical frequency of pulsation combined with fatigue, however, enables measurements to be made with quite conclusive accuracy. The sharp-peaked character of the elevation of the fatigue curves, together with the very restricted range of frequencies disturbed, seem sufficient to remove from the resonance theory the objection urged by Watt.

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* Watt, 'Psychology of Sound,' p. 142, 1917.

† Helmholtz, 'Sensations of Tone,' p. 144

‡ *Loc. cit.*

Fig. 5.

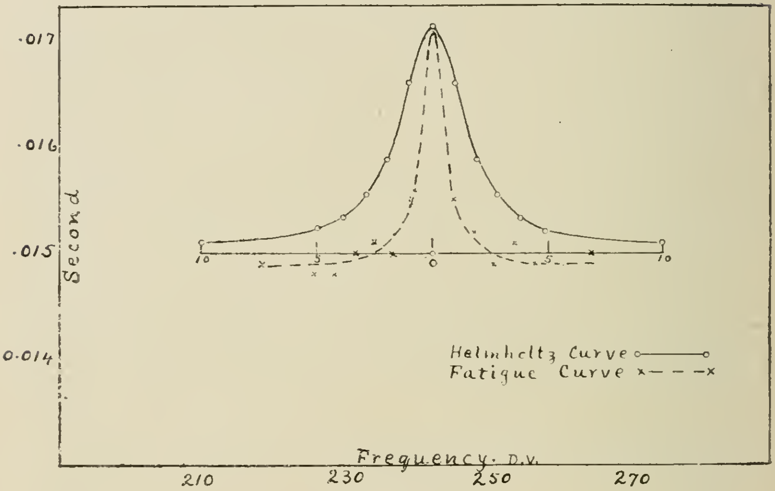

Table V.

Comparison of Helmholtz's Intensity Curve with Fatigue Curve.

P.	N′.	N.	D. Sec.
B. 1·78 cm.	218·4	242·8	0·0148
,,	226·0	,,	·0148
,,	228·7	,,	·0148
,,	231·6	,,	·0150
,,	234·5	,,	·0151
,,	237·0	,,	·0150
,,	240·0	,,	·0156
,,	242·8	,,	·0171
,,	245·5	,,	·0155
,,	248·2	,,	·0152
,,	251·0	,,	·0149
,,	254·0	,,	·0151
,,	256·8	,,	·0149
,,	265·0	,,	·0150

A. Helmholtz's Curve plotted from data in 'Sensations of Tone,' p. 144.

As pointed out above, the experiments herein described are limited to the octave from 142 to 284 vibrations. If the character of the fatigue curves is the same in the octaves below as well as above, we can explain a well-known phenomenon in music.

It is universally recognized that shakes and runs in the bass are not clear, but that the tones merge into each other. This is independent of the instrument upon which they are played. Helmholtz[*] explains this as follows:—" . . . . . . Since the difficulty of shaking in the bass is the same for all instruments; and for individual instruments is demonstrably

TABLE VI.

Normal Curves.

Frequency N.	Duration D.	Pressure. P.	Frequency N.	Duration D.	Pressure P.
	Sec.			Sec.	
A. 142·0	0·0185	1·25 cm	F. 143·0	0·0206	1·82 cm
164·0	·0172	..	167·0	·0193	..
186·0	·0160	..	190·0	·0182	..
208·0	·0149	..	214·0	·0170	..
230·0	·0139	..	237·0	·0161	..
252·0	·0130	..	260·5	·0153	..
264·0	·0127	..	284·0	·0146	..
B. 142·5	0·0194	1·45 cm.	G. 143·0	0·0210	1·58 cm.
165·5	·0181	..	167·0	·0195	..
187·5	·0168	..	190·0	·0184	..
210·0	·0157	..	214·0	·0173	..
235·0	·0146	..	237·0	·0163	..
256·7	·0137	..	260·5	·0154	..
278·0	·0130	..	284·0	·0148	..
C. 142·8	0·0197	1·53 cm	H. 143·0	0·0211	2·10 cm
165·8	·0184	..	167·2	·0200	..
188·8	·0172	..	190·2	·0187	..
211·8	·0161	..	214·2	·0177	..
235·7	·0152	..	237·2	·0166	..
257·9	·0143	..	260·7	·0158	..
280·5	·0138	..	284·2	·0151	..
D. 142·9	0·0201	1·62 cm.	I. 143·2	0·0212	2·20 cm.
166·2	·0187	..	167·3	·0203	..
189·0	·0177	..	191·0	·0190	..
212·0	·0166	..	214·6	·0180	..
235·3	·0155	..	238·0	·0171	..
258·2	·0146	..	261·2	·0160	..
280·9	·0140	..	284·2	·0155	..
E. 143·0	0·0203	1·70 cm	J. 143·5	0·0215	2·40 cm.
166·6	·0190	..	168·2	·0205	..
189·7	·0179	..	191·2	·0192	..
213·2	·0168	..	215·0	·0181	..
236·2	·0158	..	238·3	·0173	..
259·3	·0149	..	261·9	·0163	..
283·0	·0143	..	285·0	·0156	..

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[*] 'Sensations of Tone,' p. 143.

independent of the manner in which the tones are produced, we are forced to conclude that the difficulty lies in the ear itself. We have, then, a plain indication that the vibrating parts of the ear are not damped with sufficient force and rapidity to allow of successfully effecting such a rapid alternation of tones."

According to the experimental evidence of the fatigue curves, the blurring or merging together of tones in the bass is not due to the peculiar construction of the ear, nor to insufficient damping of the resonance mechanism, but is the natural consequence of the fact that the tones of the scale are not separated by absolute numbers of vibrations, but by numbers determined by fixed ratios.

The difference in vibration frequency between two successive tones in the treble is very large when compared with the difference between two such tones in the bass; for example, the difference between *c''*, 512, and *d''*, 576, is 64 vibrations, whereas the difference between C_1, 32, and D_1, 36, is only 4 vibrations. In a run in the treble, therefore, each tone is so far moved from the one preceding that the arches stimulated by the first tone are altogether outside the region of influence of the second. It can very clearly be seen therefore that, when *c''*, *d''*, *e''*, *f''*, etc. are sounded in rapid succession, the effect will be distinct and brilliant. And the higher the pitch of notes with which the runs and trills are made, the more distinct will each tone be from the other, and the more brilliant the total impression.

In the bass, on the other hand, the opposite will be the case. The difference between two successive tones is comparatively very small. As previously noted, the difference between C_1 and D_1 is only 4 vibrations, while an octave higher it is only 8 vibrations. Since the difference in frequency between consecutive tones is so small, many of the arches responding to one tone will also respond to the other; in fact, nearly the same range will be influenced by each tone. The arches most strongly affected will be the resonals of each tone, and these are themselves not far distant from each other. In fig. 1, in which fatigue curves for five frequencies at the same pressure are shown, it will be noticed that the elevations for 152 and 163 overlap to some extent. The difference in frequency in this instance is eleven vibrations. If the difference in frequency were smaller, the overlapping would be greater; therefore the farther down in the bass one attempts to produce a rapid succession or alternation of tones, the more nearly will the same range of resonators be influenced by adjacent tones, and the more indistinct and blurred will be the general impression. If semitones are employed instead of tones, the indistinctness will be proportionately increased.

The results of this investigation seem to find their natural explanation in terms of the resonance theory of audition, and therefore no present attempt has been made to interpret them in accordance with the Wrightson displacement theory.

This research was conducted under the auspices of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, to which body we wish to express our thanks.

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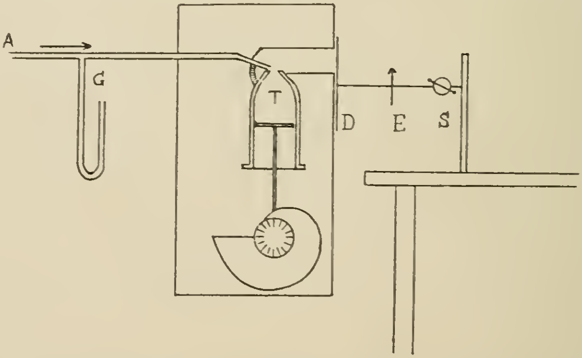
ON THE CRITICAL FREQUENCY OF PULSATION OF TONES.

On the Critical Frequency of Pulsation of Tones. *By* MOLLIE WEINBERG, *M.A., M.Sc., Research Student of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, and* FRANK ALLEN, *Ph.D., F.R.S.C., Professor of Physics, University of Manitoba* *.

THE successful application of the principle of the persistence of vision, or the critical frequency of flicker, to the study of problems of colour vision suggested the probable value of the analogous principle of the persistence of audition to the solution of problems of the perception of sound. In this communication the results of some investigations based on this latter principle are described, which show that the method is capable of extension to some of the phenomena of physiological acoustics.

Fig. 1.



The experimental arrangements, fig. 1, were similar to those used in investigations in Colour Vision †.

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* Read at the meeting of the Royal Society of Canada, Ottawa, May 1922.

† Phys. Rev. vol. xi. p. 257 (1900); Phil. Mag. vol. xxxviii. p. 55 (1919).

The source of sound was a Stern Tonvariator, T, placed inside a box lined with very soft thick felt, through which at a suitable place a hole was cut. The tonvariator was blown by a stream of air from a large constant-pressure tank, and the pressure was further regulated by suitable cocks, and measured by a small water-gauge, G. The periodic interruption of the continuous sound into separate pulses was effected by the rotation of a light aluminium disk, D, with four symmetrically placed holes of the same size as that in the box. For this purpose an electric motor was used, which was connected with a storage battery to secure exact regulation of the speed. A speed counter, S, making electric contact every fiftieth revolution of the disk, and a clock beating half seconds, were connected with a chronograph from which the speed of the disk, and hence the critical frequency of pulsation, or flutter, of the sound was computed when it became just continuous to the ear.

The ideal disk should completely interrupt the sound ray except when its openings coincide with that in the box from which the sound is issuing. To secure this, the disk might be made of the most inelastic material possible. But it is also essential that it should be very light, to permit rapid adjustment for the critical frequency of pulsation, or flutter, of the sound. A thin aluminium disk was chosen, as stated above, which was covered with velvet to dampen the vibrations as far as possible. The velvet served another purpose also, since the disk could be placed so close to the box that the velvet pile just grazed its surface. It is remarkable how greatly the intensity of the sound escaping between the box and the disk is lowered by eliminating the last slight distance between them. The ear of the observer—in this arrangement of apparatus the left was most conveniently used—was always placed in the same position, E, so that variations in the intensity of sound could not be attributed to any condition other than the rotation of the disk.

The tonvariator* is a simple König resonator with a movable bottom acting like a piston. To regulate the pitch of the tone, the piston is moved by a pin resting on the edge of a brass plate cut in a spiral of such a form that the frequencies may be read directly on an evenly-graduated circular disk rigidly attached to the spiral. The tonvariator was capable of giving pure tones of considerable variation in intensity covering the octave from 150 to 300 double vibrations per second. Since the frequencies of the tonvariator varied with the blowing pressure, it became necessary to obtain calibration curves from standard tuning forks. These curves were exact straight lines. The corrected frequencies ranged from 142 to 285 vibrations. The intensities were those obtained with air-pressures from 1·25 to 2·40 cm. of water. Above and below these pressures the tones were not sufficiently pure for experimental purposes.

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* *Physikalische Zeitschrift*, vol. v. p. [illegible] (1904).

The greatest care was taken to eliminate all extraneous noises in motor, disk, and chronograph. But it was found impossible with such arrangements as were available at the time to prevent some sound escaping from the surface of the box and through the disk. The rotation of the disk produced marked variation of the intensity of the sound ray, but the ideal sudden transition from silence to full intensity, as from darkness to light, was by no means realized. No doubt great improvements are possible in the control of sound, which we have found the most difficult part of the problem.

In making the measurements the tonvariator was adjusted to give a steady sound of the desired pitch and intensity. The ear was then placed at the proper place and the speed of the disk increased so that the interrupted pulses of sound became fused into a just continuous sensation. The chronograph circuits were then closed and the readings recorded. Each record gave several measurements, from which mean values of the critical frequency of pulsation were obtained. Each point on the curves is the mean of about ten measurements obtained from three or four independent determinations.

For each pressure or intensity of sound such measurements were made for seven frequencies extending through the octave. Ten pressures also were used between the limits mentioned above. These measurements are recorded in Table I., from which the corresponding normal curves are plotted in fig. 2. Each normal curve represents the relation between the vibration frequency, N, and the duration of the tone at the critical frequency of pulsation, D, for the octave mentioned, at a definite pressure or intensity of sound, P, when the ear was in its normal unfatigued condition. The ten normals form a regular family of curves, all being slightly convex toward the axis of frequencies.

The lowest curve of the group is that obtained with the least pressure or intensity of sound, and the highest with the greatest pressure or intensity. It has been shown by Love and Dawson * that the intensity of sound emitted by a

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* Phys. Rev. vol. iv. p. 49 (1919).

Table I.

Normal Curves Corrected for Frequency.

	N.	D.	P.		N.	D.	P.
A.	142·0	0·0185	1·25 sec.	F.	143·0	0·0206	1·82 sec.
	164·0	·0172			167·0	·0192	
	185·0	·0160			190·0	·0182	
	208·0	·0149			214·0	·0170	
	230·0	·0139			237·0	·0160	
	252·0	·0130			260·0	·0151	
	264·0	·0127			284·0	·0146	
B.	142·5	0·0194	1·43 sec.	G.	143·0	0·0210	1·98 sec.
	165·5	·0181			167·0	·0195	
	187·5	·0168			190·0	·0184	
	210·0	·0157			214·0	·0172	
	235·0	·0146			237·0	·0163	
	256·7	·0137			260·5	·0154	
	278·0	·0130			284·0	·0148	
C.	142·8	0·0197	1·57 sec.	H.	143·0	0·0211	2·10 sec.
	165·8	·0184			167·2	·0200	
	188·8	·0172			190·2	·0187	
	211·8	·0161			214·2	·0177	
	235·7	·0152			237·2	·0165	
	257·9	·0143			260·7	·0158	
	280·5	·0135			284·2	·0151	
D.	142·9	0·0201	1·62 sec.	I.	143·2	0·0212	2·20 sec.
	166·2	·0187			167·3	·0203	
	189·0	·0177			191·0	·0190	
	212·0	·0166			214·6	·0180	
	235·3	·0155			238·0	·0171	
	258·2	·0146			261·2	·0160	
	280·9	·0140			284·2	·0155	
E.	143·0	0·0203	1·70 sec.	J.	143·5	0·0215	2·30 sec.
	166·6	·0190			168·2	·0205	
	189·7	·0179			191·2	·0192	
	213·2	·0168			215·0	·0184	
	236·2	·0158			238·5	·0173	
	259·3	·0149			261·9	·0163	
	283·0	·0143			285·0	·0156	

resonator is proportional to the blowing pressure. Assuming this to be true for the form of resonator used in this investigation, the curves in fig. 2 may be regarded as indicating definitely the relation between the vibration frequency, the duration of the tone at the critical frequency of pulsation, and the intensity of the tone.

It is worthy of remark that in the analogous normal persistency curves for spectra * of varying intensities the opposite condition prevails. With light the brightest colours give the lowest curve, that is, they have the smallest values

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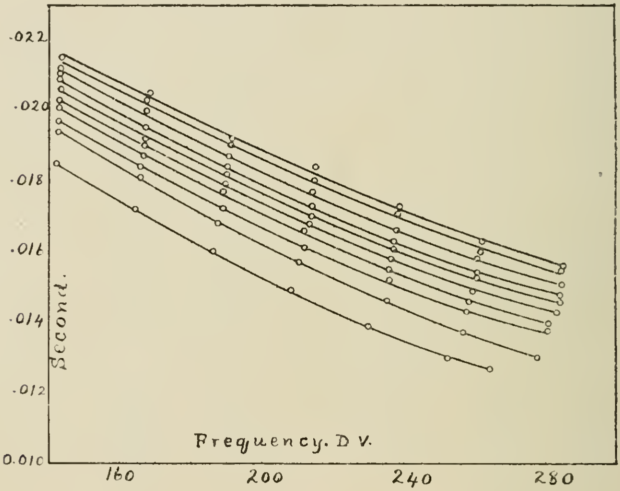
* Phil. Mag. vol. xxxviii. p. 81 (1919).

of the duration of the light at the critical frequency of flicker; whereas in sound the greatest intensities have the largest values of the duration of the tone at the critical frequency of pulsation. The mechanisms in the two sets of phenomena are widely different. Vision probably results from photo-electric action on the nerves; in sound the auditory nerves are excited by mechanical vibrations.

Fig. 2.



A somewhat similar investigation to that described above was made by Mayer *. His method was as follows: between a vibrating tuning fork and its resonator he interposed a revolving disk with openings of the same shape as that in the resonator, so that the sound was heard loudly when an opening in the disk came in front of that in the resonator, and faintly when the latter was covered. He found that his measurements conformed to the law

$$D = \frac{K}{N} + C,$$

where D is the duration of the tone at the critical frequency of pulsation, N the frequency of the fork, and K and C are constants.

The measurements given in Table I. were tested by this law and found, when plotted, not to give straight lines.

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* Silliman's Journal, ser. 3, vol. viii. (1874); Helmholtz, 'Sensations of Tone' (Eng. Trans.), p. 417.

The graphs possessed a slight regular curvature very similar to that of the normal curves in fig. 2, but opposite in sign. No doubt the time of duration of the sound at the critical frequency of pulsation and the frequency of the tone are connected in some inverse relation. The precise nature of that function, as will later be discussed, appears to be

$$D = \frac{K}{\sqrt{\log N}} + C$$

where the letters D, N, K, C have the same significance as above.

The difference between Mayer's relation and that here obtained is probably due to his method of interposing a resonator between the source of sound and the ear, whereas in our experiments the fusion of sounds was effected in the ear directly. Another possible explanation of Mayer's results is given in a later communication, "On the Effect of Aural Fatigue" *.

It will be noticed in fig. 2 that the vertical distances between the normal curves are not equal. The interval between the curves for the highest intensities is small, and gradually increases as the intensity is decreased. This suggested the possibility that some law connecting the duration time at the critical frequency of pulsation and the intensity of the sound might be deduced.

In colour vision, Ferry † and Porter ‡ found that the relation between the duration, D, of a flash of colour upon the retina at the critical frequency of flicker and the luminosity, L, was expressed by the equation

$$D = \frac{1}{K \log L}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{Ferry})$$

or

$$n = K \log L + C \quad . \quad . \quad . \quad . \quad . \quad (\text{Porter})$$

where n is the reciprocal of D, and K and C are constants. This equation is independent of the wave-length of the light.

As we have seen, the intensities of sounds and their duration at the critical frequency of pulsation have a direct and not an inverse relationship, as is the case in colour vision. Several equations suggested by the above were tried without success.

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* P. 126.

† Amer. Jour. Sci. (3), vol. xliv. p. 193 (1892).

‡ Proc. Roy. Soc. vol. lxx. p. 313 (1902).

That which appears to give the best result is

$$D = K\sqrt{\log P} + C$$

where D is the duration of the sound at the critical frequency of pulsation, P the blowing pressure to which the intensity of the sound is proportional, N the frequency of vibration of the tone, and K and C are constants.

In fig. 3, plotted from the values in Table II., the critical frequencies of pulsation are plotted against the square roots of the logarithms of the pressure. The resulting curves are, in all five cases, straight lines.

Fig. 3.

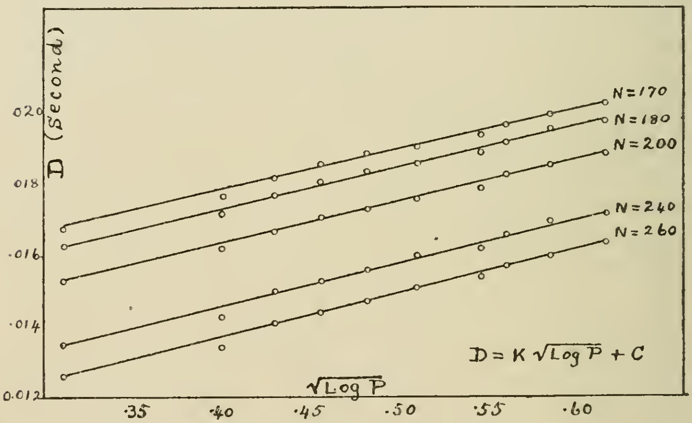


TABLE II.

Pressure P.	$\sqrt{\log P}$.	D. N=170. sec.	D. N=180. sec.	D. N=200. sec.	D. N=240. sec.	D. N=264. sec.
2·40 cm.	0·616	0·0203	0·0198	0·0189	0·0172	0·0164
2·20 ,,	·585	·0200	·0196	·0186	·0170	·0160
2·10 ,,	·560	·0197	·0192	·0183	·0166	·0157
1·98 ,,	·546	·0194	·0189	·0179	·0162	·0154
1·82 ,,	·510	·0191	·0186	·0176	·0160	·0151
1·70 ,,	·482	·0189	·0184	·0173	·0156	·0147
1·62 ,,	·456	·0186	·0181	·0171	·0153	·0144
1 53 ,,	·430	·0182	·0177	·0167	·0150	·0141
1·45 ,,	·401	·0177	·0172	·0162	·0143	·0134
1·25 ,,	·0311	·0168	·0163	·0153	·0135	·0126

A further test was made. The tonvariator was maintained constant at three different frequencies in succession, and the pressures adjusted for eight successive values in each case. The frequencies used were 170, 200, and 240 vibrations.

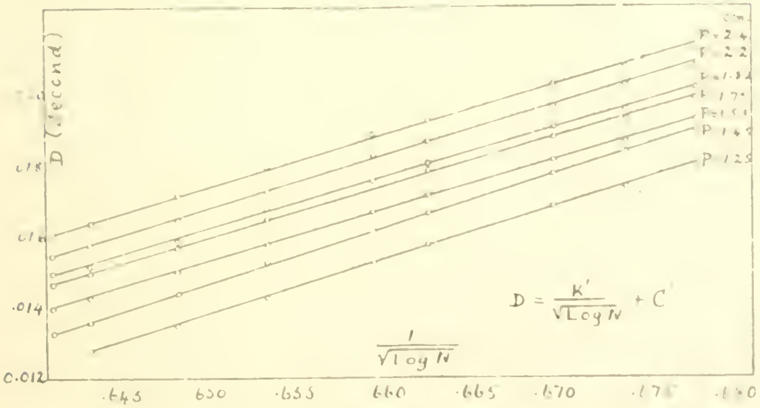
The data obtained are incorporated in Table II. with those for the same frequencies taken from the normal curves. The straight lines in fig. 3 are therefore the result, not only of data taken from the normal curves, but also of data obtained directly from independent measurements. This forms a more complete verification of the law that, at the critical frequency of pulsation, the duration of a pulse of sound varies directly as the square root of the logarithm of the pressure or intensity.

Further investigations were made concerning the relation between the critical frequency of pulsation, D, and the frequency of the tone, N, when the pressure remained constant. It will be remembered that Mayer had expressed that relation in the form

$$D = \frac{K}{N} + C.$$

On applying new data obtained in this investigation, the above law does not hold. The only manner in which Mayer's equation agrees with data here obtained is in the fact that both indicate an inverse relationship. The precise nature of this inverse function was not at first apparent. After trying a number of equations, however, we find the one that appears to give the best results to be

Fig. 4.



$$D = \frac{K'}{\sqrt{\log N}} + C'$$

where D and N have same meaning as previously, and K' and C' are arbitrary constants. In fig. 4, plotted from the data in Table III., the time values of the critical frequencies of pulsation are plotted against the reciprocals of the square roots of the logarithms of the frequencies, and again, the results are seen to be very consistent straight lines.

Table III.

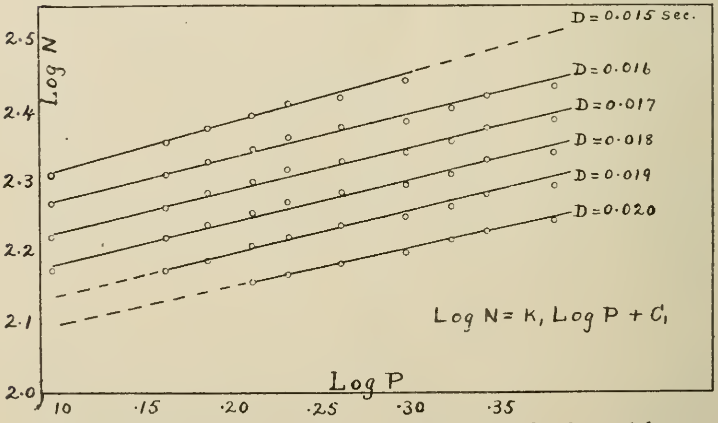
N.	$\frac{1}{\sqrt{\log N}}$.	D. P= 2·40 c. sec.	D. P= 2·10 c. sec.	D. P= 1·82 c. sec.	D. P= 1·70 c. sec.	D. P= 1·53 c. sec.	D. P= 1·45 c. sec.	D. P= 1·25 cm. sec.
150	0·6779	0·0213	0·0208	0·0202	0·0199	0·0193	0·0190	0·0180
160	·6739	·0208	·0203	·0196	·0194	·0187	·0184	·0174
170	·6698	·0203	·0197	·0191	·0189	·0182	·0177	·0168
190	·6627	·0193	·0187	·0181	·0179	·0172	·0167	·0158
200	·6596	·0189	·0183	·0176	·0173	·0167	·0162	·0153
220	·6536	·0180	·0173	·0168	·0165	·0158	·0153	·0143
240	·6485	·0172	·0166	·0160	·0156	·0150	·0143	·0135
260	·6435	·0164	·0158	·0152	·0150	·0143	·0136	·0128
270	·6414	·0161	·0155	·0150	·0147	·0140	·0133	...

It is very interesting to note that whereas D varies directly as the root of the logarithm of P when N remains constant, it varies inversely as the root of the logarithm of N when P remains constant. The square root of the logarithm seems to be involved in both relations.

This suggested the possibility of some simple relationship existing between N and P at a constant value of the frequency of pulsation, D. For this purpose, horizontal cross-sections were taken through the family of curves in fig. 2. Again, after many attempts had been made, the following equation seemed to give the best results:

$$\log N = K'' \log P + C'',$$

Fig. 5.



In fig. 5, values taken from Table IV., the logarithms of the frequencies were plotted against the logarithms of the pressures. The resulting lines, although not as consistently straight as those representing the other relations, seem to verify the equation.

TABLE IV.

P	Log P.	N.	Log N	N.	Log N.	N.	Log N
		D = 0·0150 sec.		D = 0·0160 sec.		D = 0·0170 sec.	
1·25 cm	0·0969	205	2·312	186	2·270	167	2·223
1·45 ,,	·1614	226	2·354	204	2·310	181	2·258
1·53 ,,	·1847	239	2·378	214	2·330	193	2·286
1·62 ,,	·2095	248	2·394	223	2·348	201	2·303
1·70 ,,	·2305	259	2·413	231	2·364	208	2·318
1·82 ,,	·2601	263	2·420	238	2·377	214	2·330
1·98 ,,	·2967	276	2·441	244	2·387	220	2·342
2·10 ,,	·3222	...	...	254	2·405	228	2·358
2·20 ,,	·3424	...	...	265	2·423	238	2·377
2·40 ,,	·3802	...	...	273	2·436	244	2·387
		D = 0·0180 sec.		D = 0·0190 sec.		D = 0·0200 sec.	
1·25 cm	0·0969	150	2·176	...	...	...	...
1·45 ,,	·1614	167	2·223	150	2·176		
1·53 ,,	·1847	174	2·241	155	2·190	...	
1·62 ,,	·2095	181	2·258	162	2·210	144	2·158
1·70 ,,	·2305	187	2·272	167	2·223	148	2·170
1·82 ,,	·2601	193	2·286	173	2·238	153	2·185
1·98 ,,	·2967	198	2·297	178	2·250	158	2·199
2·10 ,,	·3222	205	2·312	184	2·265	165	2·217
2·20 ,,	·3424	214	2·330	192	2·283	171	2·233
2·40 ,,	·3802	220	2·342	197	2·294	176	2·246

The three laws, therefore, which we have tentatively deduced are:—

$$D = K\sqrt{\log P} + C\ ; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$D = \frac{K'}{\sqrt{\log N}} + C'\ ; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\log N = K''\log P + C''. \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Were it not that the C's in equations (1) and (2) are apparently different, the two equations might be put together in the form

$$D = K\frac{\sqrt{\log P}}{\sqrt{\log N}}.$$

This equation would define an acoustical surface, analogous in many respects to the well-known thermo-dynamic surface, each point on this acoustical surface denoting a relation between the pressure or intensity, the frequency of the tone, and its critical frequency of pulsation.

The above is an interesting conjecture, which might lead, on fuller investigation, to fruitful results.

The range of pressures and frequencies in this investigation was small, and before the above "laws" can be accepted with confidence they should be tested through a far greater range of intensities and frequencies than the apparatus used in this investigation afforded.

An attempt was made to determine whether normal measurements of other observers correspond with those here obtained, *i. e.*, whether the sensitivity to intensity and the duration of tones are the same for the average ear. Normal curves of four other observers have so far been obtained. These are shown in fig. 6, with the data from which they were plotted in Table V.

Fig. 6.

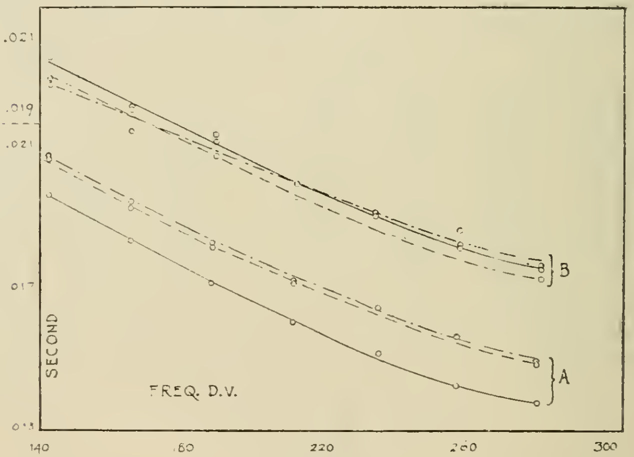


TABLE V.

Normal Curves of Other Observers.

A. N.	D. (M.W.).	P.	P.	D. (E.W.).	P.	D. (H.W.).
	Second.			Second.		Second.
142·8	0·0197	1·53 cm.	1·53 cm.	0·0207	1·53 cm.	0·0208
165·8	·0184	,,	,,	·0193	,,	·0195
188·8	·0172	,,	,,	·0182	,,	·0184
211·8	·0161	,,	,,	·0172	,,	·0173
235·7	·0152	,,	,,	·0165	,,	·0165
257·9	·0143	,,	,,	·0157	,,	·0157
280·5	·0138	,,	,,	·0149	,,	·0150
B.	(M.W.).			(S.G.L.).		(A.H.).
143·0	0·0206	1·98 cm.	1·88 cm.	0·0200	1·90 cm.	0·0198
166·0	·0192	,,	,,	·0185	,,	·0191
190·0	·0182	,,	,,	·0178	,,	·0184
213·0	·0170	,,	,,	·0165	,,	·0170
236·0	·0161	,,	,,	·0162	,,	·0162
259·0	·0153	,,	,,	·0152	,,	·0157
282·0	·0146	,,	,,	·0143	,,	·0147

The broken lines and the dot-dash curves are those of the other observers; the continuous curves are those of one of the authors (Weinberg) and are inserted for the sake of comparison. The data are also given in Table V.

The curves are divided into two groups; those in group A were obtained at approximately the same pressure or intensity; those in group B at different pressures or intensities.

The general slope of all the curves in both groups is very nearly the same. The very slight difference in curvature of the two curves in group B, as seen by their intersection at a very minute angle, may perhaps be attributed to the inexperience of the other observers.

Assuming the ears of all the observers to be average, this approximate sameness of the general slope may be taken to indicate that the degree of decrease in the duration of a tone, as its vibration frequency or pitch becomes higher, is very nearly the same for the average ear.

The relative vertical displacement of the curves in group A indicates that so-called normal ears are not equally sensitive to sounds of the same intensity, since the duration of tones of the same pitch at the critical frequency of pulsation differs.

In similar investigations in colour vision it was found that in persons between about eighteen and fifty-five years of age the sensitivity of normal eyes to the intensity of illumination is the same*. In audition, however, the sensitivity of the average ear to the intensity of tone varies. This difference is very probably due to the wide difference in the character of the two mechanisms or processes involved. The perception of light is most probably a photo-electric or chemical effect—a reaction of atoms and molecules to the stimulation of light-waves. Hence it is to be expected that for a constant intensity of stimulation there would be approximately constant atomic interactions, *i.e.*, approximately constant sensitivity. In the case of audition, however, the instrument of tone perception, the ear, is an extremely complicated mechanical structure, and therefore subject to many sources of defect or of difference. And in a mechanism so minute and delicate as the ear, it would be little less than miraculous were the mass, elasticity, and other physical properties of its component parts found always to be the same†.

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* Ferry, Am. Journ. Sci. vol. xlv. (1892).

† Seashore, 'Psychology of Musical Talent,' p. 81.

We desire to express our thanks to Prof. J. C. McLennan, F.R.S., of Toronto University, for the loan of Standard König Tuning Forks used for calibration of the tonvariator.

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On the Effect of Fatiguing the Ear with Combinations of Two or more Tones. *By* MOLLIE WEINBERG, *M.A., M.Sc., University of Manitoba, Winnipeg, Research Student in Physics of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa* *.

IN this communication, the method of studying the effects of aural fatigue by the critical frequency of pulsation or flutter of tones is applied to fatigue with two and three tones simultaneously.

The experimental arrangements were the same as described in previous communications †, except in one particular. In the former work, the source of continuous sound—a Stern Tonvariator—was enclosed in a large wooden box lined with thick felt. The box, however, transmitted some of the sound, so that the rotating disk did not completely produce the ideal alternations of sound and silence. In these experiments the upper part of the tonvariator was enclosed in a box made of pressed fibre, which is an extremely poor transmitter of sound. Watson ‡ found that a plate of this material, one-quarter of an inch in thickness, was capable of transmitting only one-tenth of one per cent. of the sound. Accordingly, a box of suitable size and shape was constructed of the fibre, in one side of which a circular hole was cut, through which the continuous stream of sound issued. Periodical interruption of the sound-ray was effected by a rotating disk in which were four symmetrically placed holes similar to that in the box. This arrangement gave sharp and clear flutterings of the tone, and, in consequence, the speed of the disk could be accurately and rapidly adjusted to the critical frequency of flutter, so that the pulsations of sound appeared just continuous. Unfortunately, the dimensions of the box interfered to some extent with the range of frequencies that could be studied, and consequently only part of one octave of tones could be employed. For the investigations described in this communication, however, it served the purpose extremely well.

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* Communicated by Prof. F. Allen, M.A., Ph.D. Read at the meeting of the Royal Society of Canada, Ottawa, May 1923.

† "On the Critical Frequency of Pulsation of Tones," *supra*, p. 50.

‡ Physical Review, vol. vii. p. 125 (1916).

I. *Application of the Critical Frequency of Pulsation of Tones to Tone Analysis.*

In a former paper* it was found that, when the ear was fatigued by exposure to any tone, the duration of the tone at the critical frequency of flutter or pulsation was increased over a range of about eight vibrations on each side of the frequency of the fatiguing tone. When similar measurements were made with the ear in its normal unfatigued condition, and the two plotted together, the fatigue curve appeared as a sharp elevation upon the normal, the peak of the elevation occurring at the frequency of the fatiguing tone.

In the experiments herein described, two or three additional tonvariators were used to give simultaneous fatigue with two or three tones of determined frequencies. Suitable calibrations of these instruments were made so that the exact frequencies were determined.

The arrangement of apparatus is shown in fig. 1, in which A indicates the air current, G the pressure gauge, T the tonvariator, D the disk, E the ear, and S the speed counter.

The method of procedure was as follows:—

At a definite blowing-pressure the tonvariator upon which measurements were to be made was adjusted to give a tone of definite pitch. The tonvariators used for the purpose of fatigue were then accurately tuned with it by eliminating beats, after which they were adjusted to give tones of desired frequencies. The left ear was then fatigued with these tones for two minutes by holding it close to the orifices of the tonvariators. Immediately afterwards the measurement of the critical frequency of pulsation, or flutter, of a tone within the fatigued range of frequencies was made. The fatiguing process was again and again repeated, and similar measurements made at close intervals, over a range of frequencies including, and wider than, the range defined by the outermost fatiguing tones.

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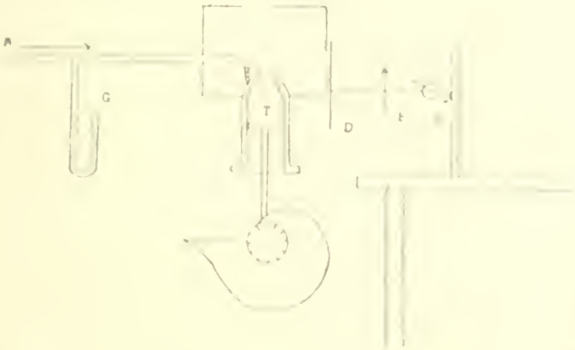
* "On the Effects of Aural Fatigue upon the Critical Frequency of Pulsation of Tones," *supra*, p. 126.

Fig. 1.

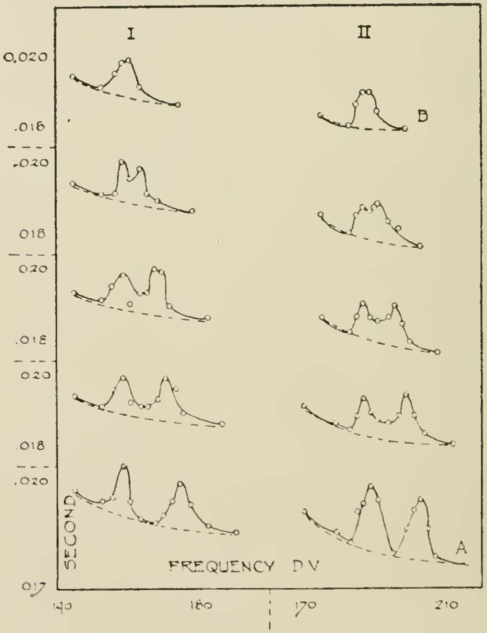


The first measurements were made with two fatiguing tones. These are tabulated in Table I., and the curves defined by them are shown in fig. 2.

The curve through the points not included in the elevation was taken to define the normal upon which the elevation is superimposed. This is indicated by the broken line. The elevation itself is similar to those obtained by fatiguing the ear with a single tone. The range affected by fatiguing, as shown by the width of the base of the elevation, is also approximately the same. In curve A the fatiguing tones were fifteen vibrations apart. Similar curves were obtained with fatiguing tones the frequencies of which, as shown in the table of values, slowly approached each other. Series I. in fig. 2 is such a set of curves. In this series the highest curve, B, was obtained with fatiguing tones that differed by two vibrations only, and curve A with tones that differed by fifteen vibrations; the intermediate curves were obtained with fatiguing tones which varied between these limits.

As can be seen from curve A, fig. 2, when the fatiguing tones are fifteen vibrations apart, there was very little overlapping in the elevations. Had they been about twenty vibrations apart, it is quite certain that each elevation would be complete and distinct from the other, one elevation beginning at the point in the normal where the other ended. Interpreted according to the resonance theory of audition, this would seem to indicate that each of the fatiguing tones would affect a different set of arches—or whatever part of the resonating mechanism responds,—which, however, were adjacent to each other. From this it may be assumed that were the differences in frequency of the fatiguing tones greater than those used for these curves, the nature of the elevations would be the same, but with an increased extent of normal curve between them—*i. e.*, the sets of arches influenced by the simultaneously fatiguing tones would be no longer adjacent, but would have a stretch of uninfluenced arches between them.

Fig. 2.



It can be seen from fig. 2, Series I., that, as the fatiguing tones approach each other, overlapping of the elevations takes place—*i. e.*, the curve between the maxima of the elevations no longer drops to the normal, but becomes more and more shallow until, when the difference in frequency is two vibrations, it has become a short, straight,

TABLE I.

Fatiguing with Two Tones simultaneously.

N. D. P.

I. Fatiguing Tones, 159 and 175.

D.V.	Sec.	Cm.
145	0·0198	1·60
153	·0195	,,
156	·0196	,,
159	·0205	,,
161	·0195	,,
164	·0190	,,
168	·0189	,,
170	·0191	,,
173	·0195	,,
175	·0200	,,
178	·0194	,,
183	·0188	,,
191	·0186	,,

Fatiguing Tones, 159 and 171.

D.V.	Sec.	Cm.
145	0·0195	1·60
153	·0192	,,
156	·0197	,,
159	·0200	,,
161	·0193	,,
164	·0192	,,
166	·0192	,,
169	·0194	,,
171	·0200	,,
174	·0197	,,
176	·0190	,,
187	·0187	,,

Fatiguing Tones, 159 and 168.

D.V.	Sec.	Cm.
145	0·0194	1·60
153	·0192	,,
156	·0196	,,
159	·0199	,,
161	·0191	,,
164	·0194	,,
166	·0194	,,
168	·0201	,,
170	·0200	,,
172	·0190	,,
183	·0187	,,

N. D. P.

I. Fatiguing Tones, 159 and 164.

D.V.	Sec.	Cm.
145	0·0195	1·65
153	·0192	,,
157	·0192	,,
159	·0201	,,
161	·0196	,,
164	·0193	,,
166	·0192	,,
169	·0190	,,
179	·0187	,,

Fatiguing Tones, 159 and 161.

D.V.	Sec.	Cm.
145	0·0195	1·65
153	·0192	,,
157	·0196	,,
159	·0199	,,
161	·0200	,,
164	·0192	,,
175	·0187	,,

II. Fatiguing Tones, 187 and 207.

D.V.	Sec.	Cm.
170	0·0192	1·55
179	·0186	,,
183	·0183	,,
185	·0192	,,
187	·0194	,,
189	·0189	,,
191	·0185	,,
195	·0180	,,
199	·0187	,,
201	·0192	,,
203	·0195	,,
205	·0187	,,
207	·0179	,,
216	·0177	,,

Fatiguing Tones, 187 and 195.

D.V.	Sec.	Cm.
170	0·0192	1·55
179	·0187	,,
183	[illegible]	,,
184	·0189	,,
187	·0194	,,

N. D. P.

II. Fatiguing Tones, 187 and 190 (contd.)

D.V.	Sec.	Cm.
189	0·0190	1·55
191	·0188	,,
194	·0187	,,
197	·0189	,,
199	·0195	,,
201	·0180	,,
204	·0181	,,
212	·0181	,,

Fatiguing Tones, 187 and 196.

D.V.	Sec.	Cm.
175	0·0187	1·55
183	·0183	,,
185	·0187	,,
187	·0191	,,
189	·0187	,,
191	·0186	,,
194	·0187	,,
196	·0190	,,
198	·0185	,,
200	·0180	,,
208	·0177	,,

Fatiguing Tones, 187 and 191.

D.V.	Sec.	Cm.
175	0·0188	1·55
183	·0181	,,
185	·0186	,,
187	·0188	,,
189	·0187	,,
190	·0188	,,
191	·0189	,,
194	·0184	,,
197	·0182	,,
205	·0177	,,

Fatiguing Tones, 187 and 189.

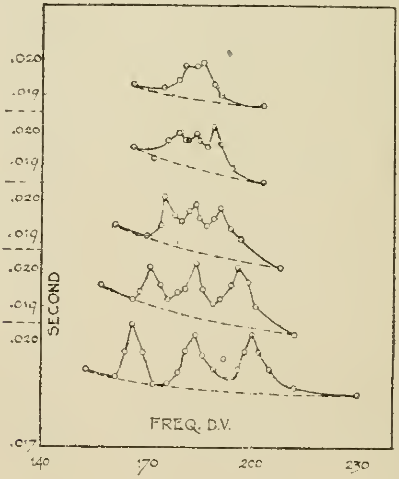
D.V.	Sec.	Cm.
175	0·0185	1·55
183	·0184	,,
185	·0185	,,
187	·0191	,,
189	·0191	,,
191	·0187	,,
194	·0182	,,

horizontal line. In other words, as the fatiguing tones approach each other, more and more of the arches responding to the one tone will simultaneously be under the influence of the other fatiguing tone until, when the fatiguing tones are very close together, approximately the same range is influenced by each.

Fig. 2, Series II., is a set of curves obtained in a similar manner to Series I., which shows the same effects over a range of frequencies higher up in the octave. It serves, therefore, as a confirming experiment. The data are also given in Table I., in which N is the frequency, D the duration of the tone at the critical frequency of flutter, and P is the pressure to which the intensity is proportional.

The above sets of curves seem explainable by no other than a resonance theory. The evidence afforded by them may therefore be taken as strongly supporting the theory, that some resonating mechanism by means of which complex tones may be analysed into their components exists in the ear.

Fig. 3.



A series of experiments similar to those above described was then carried out, in which three simultaneously fatiguing tones were used. This series of curves is shown in fig. 3, and was plotted from data in Table II. The three-elevation curves exhibit the same peculiar characteristics as do the previously described two-elevation curves. Here, again, when the fatiguing tones are about sixteen vibrations apart,

Table II.

Fatiguing with Three Tones simultaneously.

Fatiguing Tones, 166, 184, and 200.

N.	D.	P.
D.V.	Sec.	Cm.
153	0·0192	1·60
161	·0190	,,
164	·0197	,,
166	·0205	,,
169	·0197	,,
172	·0188	,,
176	·0188	,,
179	·0191	,,
181	·0197	,,
184	·0202	,,
186	·0196	,,
189	·0192	,,
192	·0195	,,
196	·0192	,,
198	·0197	,,
200	·0202	,,
203	·0197	,,
205	·0192	,,
212	·0187	,,
230	·0185	,,

Fatiguing Tones, 171, 184, and 196.

N.	D.	P.
D.V.	Sec.	Cm.
157	0·0196	1·57
166	·0192	,,
168	·0184	,,
171	·0201	,,
174	·0196	,,
176	·0192	,,
179	·0194	,,
181	·0195	,,
184	·0202	,,
186	·0195	,,
189	·0191	,,
191	·0192	,,
194	·0196	,,
196	·0201	,,
199	·0197	,,
201	·0190	,,
212	·0182	,,

Fatiguing Tones, 175, 184, and 191.

N.	D.	P.
D.V.	Sec.	Cm.
161	0·0193	1·50
170	·0190	,,
173	·0194	,,
175	·0201	,,
178	·0196	,,
180	·0194	,,
182	·0197	,,
184	·0199	,,
185	·0195	,,
187	·0193	,,
189	·0195	,,
191	·0198	,,
194	·0192	,,
197	·0189	,,
208	·0181	,,

Fatiguing Tones, 179, 184, and 189.

N.	D.	P.
D.V.	Sec.	Cm.
166	0·0195	1·51
172	·0192	,,
175	·0197	,,
179	·0199	,,
181	·0197	,,
182	·0197	,,
184	·0199	,,
185	·0197	,,
187	·0195	,,
189	·0201	,,
191	·0196	,,
194	·0189	,,
203	·0185	,,

Fatiguing Tones, 181, 184, and 186.

N.	D.	P.
D.V.	Sec.	Cm.
166	0·0193	1·50
175	·0192	,,
179	·0194	,,
181	·0198	,,
184	·0198	,,
186	·0199	,,
189	·0195	,,
191	·0190	,,
203	·0187	,,

each elevation slopes down almost, if not quite, to the normal. As the differences between the frequencies of the fatiguing tones are decreased, the curves between the peaks of the elevations again recede from the normal until, when they have approached each other very closely, there is a short, straight, horizontal line between them. At that point approximately the same range of arches is influenced by each fatiguing tone, and the resonals of each—*i. e.*, those arches possessing natural vibration frequencies corresponding exactly with those of the entering tones—are adjacent to each other. In all cases, whether fatiguing with two or with three tones, the maxima of the elevations define the resonals.

The curves indicating the effects of fatigue caused by three tones are thus seen to be exactly similar in character to those for two tones. It may therefore be justifiably assumed that were the ear to be fatigued with more than three tones simultaneously, by a method of procedure similar to the one above described, a set of curves would be obtained possessing peculiarities similar to those possessed by the curves in figures 2 and 3; in all cases the highest peaks of the elevations would define the resonals—*i. e.*, the resonating arches corresponding to the frequencies of the fatiguing tones.

The above therefore indicates an altogether new and very interesting method of tone analysis. To analyse a compound tone would only necessitate repeated fatiguing with the given mixture of tones, each fatiguing process being accompanied by a corresponding persistency measurement; the entire procedure being extended over a range of frequencies within which, it is judged, the component tones lie.

II. *An Experimental Study of Differential Tones.*

Combinational tones are heard when two musical tones of different pitches are sounded together loudly and continuously. They are of two kinds—differential and summational tones. The pitch number of the differential is equal to the difference of the frequencies of the generating tones: and that of the summational tone is equal to the sum of the frequencies of the generating tones.

There are different orders of combinational tones. The differential, or combinational tone of the first order, is one of pitch equal to the difference of the vibration frequencies of the generating tones themselves. Combinational tones of the second order are formed by the combination of the generating tones with differentials of the first order. These again produce new combinational tones with other differentials. There are thus differential tones of many orders, the first-order differential being the loudest, the intensity decreasing rapidly as the order of the differential becomes higher.

This investigation deals with differential tones of the first order only.

The successful results obtained in investigating the effects of aural fatigue suggested the application of that method to determine the probable nature of the combinational tone.

The apparatus used was the same as that employed in the investigation in the first section of this paper.

The method of procedure was as follows:—

Two tonvariators were adjusted to give tones of such frequencies that their differential of the first order fell somewhere within the range of frequencies upon which measurements of the critical frequency of pulsation could be made. The true frequency of the differential tone was obtained from the calibration curves of the tonvariators made by comparison with tuning-forks. Fatiguing with the two generating tones simultaneously, and proceeding in a manner similar to that described in the previous section, measurements of the critical frequency of pulsation were made at very short intervals over a sufficiently wide range of frequencies which included the differential tone of the first order.

The resulting curves, plotted from the data in Table III.

Table III.

Differential Tones of the First Order.

A. Generating Tones, 170 and 370.
Differential Tone, 200.

N. D.V.	D. Sec.	P. Cm.
180	0·0195	1·55
190	·0191	,,
194	·0195	,,
197	·0195	,,
200	·0199	,,
203	·0191	,,
206	·0189	,,
210	·0190	,,
214	·0186	,,
220	·0185	,,

B. Generating Tones, 220 and 400.
Differential Tone, 180.

N. D.V.	D. Sec.	P. Cm.
159	0·0194	1·50
169	·0192	,,
174	·0196	,,
177	·0197	,,
180	·0199	,,
183	·0194	,,
186	·0193	,,
191	·0188	,,
199	·0186	,,

Generating Tones, 150 and 350.
Differential Tone, 200.

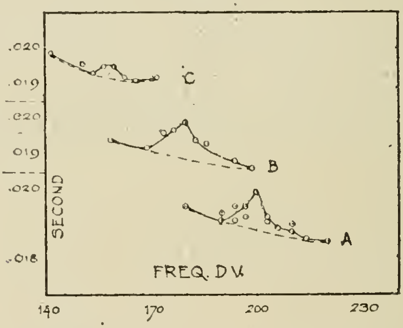
D.V.	Sec.	Cm.
180	0·0195	1·55
190	·0193	,,
194	·0191	,,
197	·0192	,,
200	·0199	,,
203	·0192	,,
206	·0189	,,
210	·0188	,,
220	·0185	,,

C. Generating Tones, 220 and 380.
Differential Tone, 160.

D.V.	Sec.	Cm.
112	0·0199	1·45
151	·0196	,,
154	·0193	,,
157	·0195	,,
160	·0195	,,
163	·0192	,,
166	·0191	,,
172	·0192	,,
182	·0191	,,

are given in fig. 4. Each graph is seen to be a portion of a normal curve, broken by a short elevation similar to that obtained by direct fatigue. The peak of the elevation is at a frequency which very closely approximates that of the differential. Curve A is the average curve drawn through two sets of measurements, both for the differential tone of frequency 200, the generating tones of each set differing by that number. The frequencies of the generating tones are given in the table. This indicates that no matter what the generating tones may be, the combinational tone will influence the same portion of the resonating system if the difference of their vibration frequencies is the same.

Fig. 4.



Curves B and C were obtained in a similar manner to A, but for differing pitches of the differential. The characteristics of all the curves appear to be the same. Curve C is a little shallower than A and B.

The position of the maximum height of the elevations represents approximately the pitch of the differentials. The vertical heights of these elevations, however, are not as great as those representing fatigue caused by ordinary tones. This difference is probably due to the comparatively low intensity of the differential tones.

The graphs discussed may, with the aid of the resonance theory of audition, be interpreted in such a manner as to explain the probable nature of the differential tone. The elevations indicate that the differentials have as direct an effect upon portions of the series of resonating arches as have tones generated in the ordinary manner—*i. e.*, differential tones are objective in character.

It was formerly believed that combinational tones were subjective effects—*i. e.*, purely psychological phenomena.

Helmholtz [*] himself stated that there were both objective and subjective combinational tones. Preyer [†] carried out a series of experiments which seemed to prove the subjectivity of differential tones. The experimental evidence as given above, however, supports the theory that differential tones of the first order are objective, since they possess the same peculiarities of stimulation as do tones produced in the ordinary manner. In other words, they are physiological and not psychological in their origin.

It was hoped to carry through a series of experiments similar to those above described for summational tones. Since this would necessitate the taking of measurements over a range of frequencies far higher than that which could be measured with the experimental arrangements at the time, their study had to be postponed until the apparatus could be improved to allow measurements to be taken over a more extended range of frequencies.

Many attempts were therefore made to adapt the apparatus to higher octaves. But with frequencies above 300 d.v. the rotating disk was incapable of giving sufficiently marked alternations of intensity of the sound to be of any value. A new method of interruption of the sound-ray was found, but it has not yet been sufficiently developed to give reliable measurements.

In conclusion, it may be stated that the results of this investigation support the theory formulated by Helmholtz, that tones are perceived and differentiated from each other by means of a resonance mechanism which exists in the internal ear. From this general statement it is also clear that differential tones and probably summational tones are not excluded.

I wish to acknowledge my indebtedness to the kindness and valuable advice of Dr. Frank Allen, Director of the Department of Physics of the University of Manitoba, at whose suggestion and under whose direction the investigations here described were carried out.

I also desire to express my thanks to the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, under whose auspices this investigation was conducted.

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[*] Helmholtz, 'Sensations of Tone,' p. 531

[†] *Loc. cit.* p. 531

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ON THE REFLEX ORIGIN OF THE SELF LIGHT OF THE RETINA

BY

FRANK ALLEN

ON THE REFLEX ORIGIN OF THE SELF LIGHT OF THE RETINA

By Frank Allen

SYNOPSIS

In this paper the characteristics of the self light of the retina are reviewed and compared with those of the light formed by reflex stimulation of the fundamental color sensations. For this purpose the numerous references to self light in Peddie's recent work on Colour Vision are made the basis of study. Reasons are given to show that the reflex theory will satisfactorily account for the self light; its color tone; the possibility of an invariable color in the spectrum; the smaller degree of saturation of a color formed by mixture of two or more colors on the retina compared with that of its simple spectral equivalent; the threshold values of colors; and the effect on self light phenomena of changes in mechanical pressure in the retina due to variations in blood pressure.

Underlying all perception of color is the presence in the retina of white light of varying intensity, the origin of which is very obscure. Also on closing the eyes it is possible to see a misty dark gray light which Helmholtz[1] described as characterized by many vascular ramifications which resemble scattered moss and leaves.

In this communication the writer has endeavoured to gather together the main characteristics of the retinal self light, and, as the title indicates, to identify it with the reflex light invariably associated with all direct applications of color to the eye.

In addition to the usual direct action exercised by all colors upon the retina, it has been shown by the writer[2] that every spectral color stimulates by reflex action the three fundamental sensations, red, green, and violet, and also enhances the sensitiveness of their receptors. In consequence, the brightness of the corresponding colors is increased to a greater or less degree according to the physical characteristics of the direct light. While the three sensations are invariably excited, the major part of the enhancement at medium intensities is in the sensations complementary to the active colored light. It is a notable fact, as an examination of the numerous curves in the paper just referred to will show, that, with the intensities of the colors there employed, the green reflex extends through the yellow, its maximum often being in the brightest part of that region. With white light the three reflexes were also evident, the green-yellow depression of the curve indicating that particular reflex to be especially well developed.

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[1] Physiol. Optik. 3rd Ed., 2, p. 12 (Eigenlicht).

[2] On Reflex Visual Sensations. J. O. S. A. & R. S. I., 7, p. 583; 1923.

The reflex enhancement of sensations is transferred from one eye to the other, and, as the writer has more recently shown,[3] from one area of a retina to those adjoining; and it occurs also in the same retinal area upon which the direct light falls and in orderly conjunction with its effects. The direct action of each color also extends to all three primary sensations, the major stimulation being with either the one or the two sensations chiefly concerned.

The consideration of the phenomena of the intrinsic or self light of the retina appears to show that the efferent nerve impulses in enhancing the receptors, at the same time cause their stimulation, with the resultant production of light to a greater or less extent.

It is generally held that equal stimulation of all three sensations causes the perception of white. Consequently the inevitable result of reflex stimulation of the three sensations is the production of white light in conjunction with every color affecting the eye. Should the three sensations be stimulated equally, the reflex white will be untinged with color; but should there be unequal excitation, the white may be somewhat tinted with one of the fundamental colors, or with such a combination as to make the white either yellowish or bluish in appearance. While every one of these results is theoretically possible, observation must determine which one is actually realized. As the efferent impulses in their nature must originate in the visual centers of the brain, the reflex white light caused thereby must be of central origin.

Since white is present in all colors, and since all colors at both extremes of intensity tend to become white with the loss of their color tone, it has been believed that whiteness itself is a separate fundamental sensation. Hering specified that one of the three hypothetical photochemical substances is for the white-black series of sensations. Wundt believed the impact of color always produced two effects, a chromatic and an achromatic. In his theory McDougall provided a separate white process. Mrs. Ladd-Franklin and also Edridge-Green consider white to be the primitive process out of which the various color preceptions have developed. Abney came to the conclusion that white is caused by the main vibration generally, and that color is as it were superposed upon it. Helmholtz considered that each color directly excited all three primary sensations, and that in consequence white must form part of the resulting perception.

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[3] Reflex Visual Sensations and Color Contrast. Jour. Op. Soc. Am., 7, p. 913; 1923.

Color theorists such as Helmholtz, Konig, Exner, and Hering, also specified that the colors they selected as primaries were to be regarded as more saturated, i.e. containing less white light, than their spectral representatives. But "it is not possible," says Peddie[4] "from phenomena of colour mixture, to determine the fundamentals. The only reason for choosing red, green, and indigo or violet, from amongst spectrum colors, as simple and fundamental colors (corresponding, that is, to fundamental sensations) is that they have the smallest admixture of white." And again (p. 67) "Rich pure color glow is the characteristic of the simple colors, say, red, green, and indigo, strong but whiter color distinguishes the fused colors yellow and pure blue." Nor will it be overlooked that purity or the degree of saturation is one of the color constants; or, as Peddie expresses it (p. 135), "The three attributes whiteness, color, and luminosity constitute the directly perceived aspects of visual sensation."

For the purpose of this study of the self light of the retina, the recent work on "Colour Vision" by Peddie is of very great service; though unfortunately the original sources of his information are but rarely indicated. From the frequency of his references to the peculiarity of vision which is the subject of this paper, it is evident that (p. 50) "the importance of the modifications of visual perception by the presence of self light" is very great. Since the self light is so insistently present and continues so long after all external stimuli have ceased, it is frequently referred to as the inherent or intrinsic luminosity of the eye. Burch (p. 46), however, found that with "prolonged resting of the eye in an absolutely dark room, the self light slowly diminishes and finally disappears."

As a deduction from mathematical theory Peddie concludes (p. 74) that "the self light constant is smaller for blue light than for red and green lights, for which the values are about equal." With this Peddie connects (p. 74) "the high sensitivity of the eye to color variation in the blue region of the spectrum." This no doubt is connected with the fact that violet is the most saturated of the spectrum colors, with ultramarine blue closely following.[5] And this in its turn is most probably due to the remarkable reflex power[6] which these colors possess.

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[4] Colour Vision (Edward Arnold & Co., 1922), p. 64. The pages indicated in the text of this paper refer to this book.

[5] Rood: Modern Chromatics, p. 165.

As stated above the composite reflex light may be white or tinged with color. At present there is no way of predetermining what its appearance will be, or whether its color will remain the same at all intensities. Peddie concludes (p. 81), again from mathematical reasoning, that the color tone of the self light, which is always present in eye observations (p. 84), must be yellowish white. In terms of the reflex theory this would imply that at low intensities the red and green sensations are excited more than the violet, which would therefore place the preponderating effect between the former, which is in the yellow. This may easily be the case; but there is no apparent reason why at high intensities equality of stimulation should not result, with complete whitening of the reflex or self light.

Peddie further says (p. 81): "This color tone, (i.e. yellowish white) of the self light is superposed on all color tones belonging to the external light. Therefore, to maintain a constant color tone with increasing intensity, the tendency of the externally caused color to become white must be checked by taking it of more and more saturated value . . . Ultimately the tendency of all colors towards white at very high intensities would swamp the effect of the self light, and even yellow would approximate to white."

But why should all colors have a tendency towards white at high intensities? This phenomenon itself requires an explanation as much as any other. From the last part of the quotation Peddie regards this "tendency towards white" as an unexplained phenomenon, yet one quite distinct from the white or yellowish white self light. But from the point of view of the reflex theory the very reverse is the case; and the reason why all colors tend to become white lies in the fact that the reflex white light itself becomes so extremely intense that it "swamps the effect" of the direct color action.

Another way of explaining this, however, may be more accurate. Since each color directly, as well as reflexly, stimulates all three sensations, there must be a maximum intensity to which each can be directly excited. When the sensation most immediately concerned has reached its maximum, further increases of intensity will be effective only upon the remaining sensations until all alike are at their maxima. This process can easily account for the disappearance of any particular color and its replacement by white. The reflex stimulation, as experiment shows, extends always to all three sensations, and hence will also produce white. The double production of white will therefore be devoid of color.

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[6] On Reflex Visual Sensations, loc. cit., p. 596.

If two or more spectrum colors form a mixture upon the retina, each will separately excite its own reflex white, and the resulting reflex or self light will be of much greater intensity than that produced by a single color. It is a principle of physiology[7] that "two reflexes making use of the same final path may reinforce one another." And also, "like reflexes mutually reinforce each other on their common path." (Sherrington.) Consequently it is not surprising "that the color obtained by mixture of two spectrum lights is whiter than the similarly colored region of the spectrum." (p. 118.) For in forming mixtures of colors upon the retina, only one area is employed and it is obvious that the reflexes excited by each color stimulus must make use of the same final path. It is therefore necessary, for example, to add white to spectral yellow in order to match a yellow formed by proper mixtures of red and green lights.

Whiteness of mixtures reaches its extreme in the case of complementary colors. For (p. 84) "complementariness is also practically determined in presence of self light." It may, however, rather be the case that the production of white self or reflex light in excess is what constitutes complementariness. For as we have just seen, two colors when mixed on the same retinal area will generate an unusually large quantity of white light. If in addition the two colors are such as will when combined directly stimulate the three sensations equally, the result must be the complete disappearance of color and its replacement by white. To accomplish this purpose the sensations must be balanced; consciousness informs us by the perception of white that the balance has been effected.

It is extremely probable from the reflex theory of Color Vision that a particular wave length will change its hue as it passes from minimum to maximum intensity. There is at present no independent determination of the growth of the individual reflexes. But it is most improbable that all three reflexes will rise to their maxima at precisely the same rate. Consequently the changes in hue will follow the relative changes in enhancement of the sensations. And if changes occur, they must always tend in normal eyes in a certain definite direction. There will probably be no color which will remain absolutely unchanged in hue as the intensity changes from minimum to maximum. If, for example, the green reflex, which usually extends to yellow, were to develop the most prominently, the colors on each side of it would tend towards green or yellow with increase of intensity. It would be consistent therefore with the reflex theory if one color at least, viz. that towards which those on each side tended, should experience a minimum change of hue under all conditions of intensity. Approximately at least, this hue would be an invariable color.

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[7] Bayliss: Principles of General Physiology, p. 507; 1920.
Sherrington: Integrative Action of the Nervous System, p. 233.

Quite in accord with this reasoning are Peddie's conclusions from his study of Helmholtz's equations, (p. 80): "As the external stimulation increases or decreases in intensity, without changes in the proportions of the fundamental stimulations, the color apparent to the eye must change in consequence of the presence of self light, supposed for simplicity to be constant in amount and quality. Even with that restriction, the change in color in passing from ordinary to very feeble, or from ordinary to very intense, illumination is in agreement with observation."

"With increasing brightness all spectrum colors, any one of which possesses a fixed relative composition with regard to the fundamentals . . . becomes more similar to white of a yellowish tinge. The most rapid passages thereto occur in the change of green into yellow, and of violet into whitish blue. Greater increase of intensity is required to change blue into white and red into yellow. The only color which remains markedly unchanged at all intensities is a yellow white."

As regards the meaning of the threshold value of color, Peddie suggests (p. 128) that it is "the value of the external stimulus which forms the least perceptible difference from the so-called self light. Behind this question lies the further one whether the threshold value is entirely due to the self light, so that it would vanish if the latter vanished; or is in part due to structural or functional conditions, so that it possesses a small finite limit under extreme dark adaptation." And in regard to the increase of the threshold value after fatigue, he says (p. 172): "The increase of the threshold value has then a positive magnitude as self light, evident during the absence of any or too strong external illumination, and which may inhibit that external illumination from perception if it be sufficiently weak, as when an eye, dazzled by strong lights, cannot perceive even bright objects through the consequent glare of the intensified self light. But the increase in the threshold value may also have inhibiting effect apart from evident self light."

Since the direct action of light or color is at least the chief agency by which reflex sensations are excited, it follows that the direct effect of light should have a threshold value apart from the self or reflex light which is occasioned by it. This would have to be tested by experiments with intermittent vision, in order that the duration of the direct stimulus on the retina can be controlled and studied before the reflex light has time to develop. But in steady light it will probably be impossible to separate threshold values from the reflex self light.

The reflex theory quite adequately accounts for "the calling out of a colored sensation, previously below the threshold, by means of a feeble white stimulus" (p. 192). For, as the writer has shown,[8] white light reflexly enhances the perception of colors in all parts of the spectrum. The sub-threshold color stimulus therefore falling upon the enhanced sensations, will as a consequence have sufficient intensity to be perceived. This amounts to the same thing as saying that "a color threshold is lowered by a process of defatigue" (p. 201). Defatigue is a term which Peddie uses frequently, and is his equivalent for what the writer has shown to be reflex enhancement of sensations; (e.g. see Peddie, p. 172). Peddie also suggests (p. 148) the possibility that the three fundamental threshold values may correspond to the components of the self light.

"In the central fovea" says Peddie (p. 147), "the sensitiveness to weak light is usually very small. Thus it is well known that faint stars which can be seen by indirect vision disappear when the gaze is direct. The natural conclusion is that the cone structure, which is effective in direct vision, is not responsive to very feeble illumination. This might be due to inherent structural or functional conditions. On the other hand, it may be due to excitation, not necessarily visible, of self light in the foveal region; which, in accordance with Fechner's modification of his law of the sensation of luminosity, effectively lessens the sensitivity to illumination . . . It is quite in consistence with this view that the slight possibility of foveal dark adaptation which is normally observable must be preceded by strong light adaptation. This accentuates the self light above its normal value."

This brings up the question whether the rods and cones are differentiated with respect to the direct and reflex sensations. So far as the

[8] Reflex Visual Sensations, loc. cit., p. 598.

writer's investigations have gone the actions of light have been spread over relatively large retinal areas in the central part of the eye. There is no experimental evidence at present as to whether the reflexes exist in the fovea, which has no rods, or whether they are found in those peripheral regions where the rods are greatly in excess of the cones. It will undoubtedly be of great interest and importance to discover the relation of the rods, cones, and visual purple, to the direct and reflex effects of color. The two actions of color, direct and reflex, the two kinds of optic nerve fibres, afferent and efferent, and the two kinds of end organs, rods and cones—receptors and effectors?—offer most suggestive possibilities for the more exact formulation of the physiological theory of color vision.

In regard to the perception of blackness Peddie is of the opinion (p. 170) that "it is the existence of this self light, whatever be its origin, which gives rise to the idea that there can be degrees of blackness . . . But we ought not to conclude," he continues, "that there can be a black which is 'blacker than black.' The error lies in calling the normal background black when external light is excluded."

The self light is usually considered to be very weak since ordinarily it is observed in darkness. But its occurrence is by no means limited to that condition. In speaking of fatigue Peddie remarks (p. 149): "When the fatigue tint becomes noticeable, the condition of dazzle arises, though the term is generally employed only when the induced self light becomes strongly noticeable."

"When the intensity of illumination of an object seen through self light or dazzle light is reduced so as not to exceed the intensity of the later by more than the limit of differential perception, the object ceases to be visible."

He also refers (p. 166) to the fact that "Fechner has shown how the influence of self light may be included in the mathematical formulation dealing with intensity, and that Helmholtz has extended the formulation so as to include the case of the influence of self light upon color, and that not merely in weak illumination, but even in the extreme case when dazzle occurs." And again (p. 167) he refers to "self light in perhaps its extreme manifestation of dazzle."

From the point of view of the reflex theory the continuous increase of self light from almost imperceptible intensity to the opposite extreme is to be expected. For all colors excite the three reflexes, thus producing white, and the magnitude of their excitation must depend, though only in part, upon the intensity of the external light. Increase of the latter can scarcely fail to augment the former up to some limiting maximum value which may be very great.

Though the intensity of the self light may fluctuate irregularly when weak (pp. 174 and 175), strong illumination will render it steady (p. 177).

In his study of the spectrum curve, Fig. 1, in the color triangle (p. 54), Peddie says (p. 55): "The sharp inflection of the extreme tip of the violet end of the curve is due, as Helmholtz pointed out, to fluorescence in the eye which makes the light falling on the retina from this region of the spectrum whiter than the actual light as it would be perceived by a non fluorescent eye."

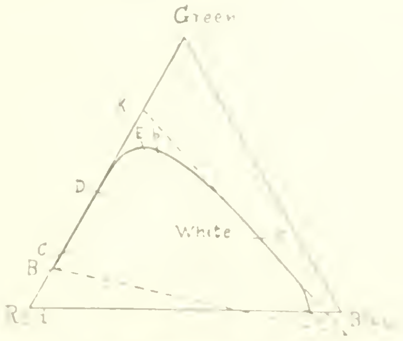

FIG. 1.—Spectrum curve in the color triangle.

In the papers already cited[9] the writer has shown that violet exerts by far the most powerful reflex influence of all colors, the effect being quite as great as that produced by yellow light which is seven hundred times as bright as the color of wave length 410μ. The inflection of the violet end of the spectrum curve may therefore be due to this exceptionally large reflex stimulation of the fundamental sensations which is easily capable of whitening the violet light.

It is impossible that fluorescence, which is a distinctly physical phenomenon, can be caused by physiological reflex action; nor can that phenomenon be produced on any part of the eye other than the area upon which the external light impinges. And it must be remembered that the same reflex effects of violet that are found in the retinal area directly stimulated by the light are found in the adjoining regions and are also transferred from one eye to the other.

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[9] On Reflex Visual Sensations, *loc. cit.* p. 596.
Reflex Sensations and Color Contrast, J. O. S. A. & R. S. I., 7, p. 925, 1923.

But since fluorescence does occur in the retina its presence suggests that some function must be performed by it. Mr. M. S. Hollenberg has suggested to me the probability that its purpose is protective to the visual apparatus. It is well known that ultra violet waves reach the retina, and if very intense are highly painful and injurious. With ordinary modes of illumination, especially with daylight for which the eye is fundamentally adapted, the quantity of ultra violet radiation is small. When this falls upon the retina it is absorbed by the fluorescent substance and transformed into harmless waves. The quantity of fluorescent material in the eye can only be very small and it is not equal to the task of transforming the powerful radiation of very short wave lengths produced by some modern artificial luminous radiators. When the protective barrier is overwhelmed the retina is helplessly exposed to danger.

Peddie also connects the self light of the retina with the phenomena of after images, observing (p. 169) that "All after images are, strictly speaking, manifestations of the so-called self light of the eye raised by precedent conditions to an intensity sufficient for direct sensation under circumstances in which it would normally be quite invisible." And again (p. 173) he speaks of "the intensified self light which constitutes the after images."

The phenomena of after images form a subject of great extent and complexity which it is the intention of the writer to consider, together with the closely allied subject of inhibition of sensations, in a future communication. Further discussion of these topics will therefore be omitted.

In accounting for the origin of the self light Peddie suggests a considerable number of possible causes (p. 48): "The apparent luminosity which is evident to the eye against the dark background of a room from which light is totally excluded depends upon the illumination which has previously fallen from external sources upon the retina. An effect of this kind might arise from fluorescence in some part of the eye, or from the persistence of that physical consequence of the illumination of the retinal structures which gives rise to the stimulation of the nerves, or from persistence of that stimulation, or from persistence of the physiological effects of that stimulation when it influences the brain organs concerned in psychological perception. On the other hand it may have its origin in the retina itself from an extraneous development therein of the physical action which results, to a still greater extent, when external light falls upon the eye: or it may originate by extraneous development of any of the energy transformations which arise in the transmitting apparatus or in the brain itself as a consequence of the incidence of external light upon the retina.

This list of suggestions obviously decides nothing, but at least it serves to indicate how difficult it has been to determine the origin of the self light. The experimental demonstration of reflex excitation of the primary sensations seems, however, to provide a simple as well as an adequate explanation of the origin of the hitherto puzzling phenomenon of the self light of the retina.

The ordinary excitation of the visual receptors is by means of external light. In addition to this there is evidence that reflex light effects are caused by mechanical pressure.

As quoted above Helmholtz states that on closing his eyes he observed the self light in forms resembling moss and leaves. He also observed it as circular and other forms of faintly luminous mists which appeared to travel towards the centre of the field of vision. The movements of these mists he observed to be synchronous with respiration.

The observations of Purkinje on the same phenomena are also referred to by Helmholtz. After vigorous physical exercise Purkinje saw in the dark field of vision a feeble light waving and flickering like a dying-out flame of spilt alcohol. On closer observation he also saw in it innumerable small points of light which moved away from each other leaving streaks of light in their paths. Every unexpected or uncertain movement and momentary oscillation of the eye is accompanied by alteration of the positions of these pale mists and other light images.

My research assistants, Messrs. A. and M. S. Hollenberg, have suggested the probability of the close connection between these phenomena and changes in the mechanical pressure on the retina arising from variations of the pressure of the blood.

It is of course common observation that a blow on the eye produces irregular flashes of light, and that a steady strong pressure also causes luminosity in the retina. Indeed the observations of Helmholtz may be readily repeated by covering the closed eyes with the hand and at the same time exciting pressure with the fingers upon the eyes.

When a person has high blood-pressure it often happens that on closing the eyes flashes of light are seen. In glaucoma the intraocular pressure is already high so that additional pressure in the form of arterial pulses may also produce flashes of light as well as circular colored rings or halos around artificial lights.

The blood-pressure in the arterial system experiences a dual alteration,[10] both elements of which are rhythmical. First, there is an increase of pressure with each heart beat causing expansion of the blood vessels, and, second, there is a greater increase of pressure with each inspiration and a fall with each expiration. The former pressure changes are much more frequent than, but not so extensive as, the latter. After exercise both heart beats and respiration are faster and more vigorous with correspondingly greater alterations in the blood-pressure. Every movement of the body seems to be reflected in altered blood-pressure. Variations in the accommodation of the eyes also change the intraocular pressure.

The movements of the streaks and spots of light and light mists, which Purkinje observed to be synchronous with respiration, and more pronounced after exercise, together with other luminous pressure effects, all serve to prove that mechanical stimulation of the retina by changes in the blood-pressure in its circulatory system is the efficient cause of these peculiarities of the self light. In these cases also the pressure is conveyed to the brain centres in the form of nerve impulses which are capable of stimulating the efferent fibres so as to produce the reflex light. As all three sensations are equally and simultaneously stimulated the reflex light is white.

From the various characteristics of the self light and the modes of its excitation, and from the properties of the sensory visual reflexes as well as the particular physiological principles in accordance with which they operate, the general conclusion seems to be warranted that the self light of the retina, which is usually seen as a feeble luminous impression in the dark, is identical in its origin with the weak as well as the bright white light underlying and accompanying all color perception, and that it is reflex in its nature.

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[10] See blood pressure tracing and explanation in Howell's Text-book of Physiology (8th Ed.), p. 656.

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Vol. 8, No. 2, February, 1924

A NEW TRI-COLOR MIXING SPECTROMETER

BY

FRANK ALLEN

A NEW TRI-COLOR MIXING SPECTROMETER

By Frank Allen

The new instrument of which a brief description is given in this communication, is a combination in part of the color mixing spectrometer described by Helmholtz in Physiol. Optik, 3rd Ed., 2, p. 333, and of the Hilger wave length spectrometer.

The plan of the instrument is shown in detail in the two accompanying figures.

In the Hilger spectrometer the collimator and telescope are fixed at right angles to each other, and the spectral ray in the axis of the telescope emerges from the peculiarly shaped prism, *A*, always at minimum deviation. The various colors are brought into view by rotating the prism, which is accomplished by means of a drum graduated in wave lengths. The prism and drum are mutually adjusted so that the wave length of the color under observation is always indicated directly by an index which runs in a helical slot in the drum.

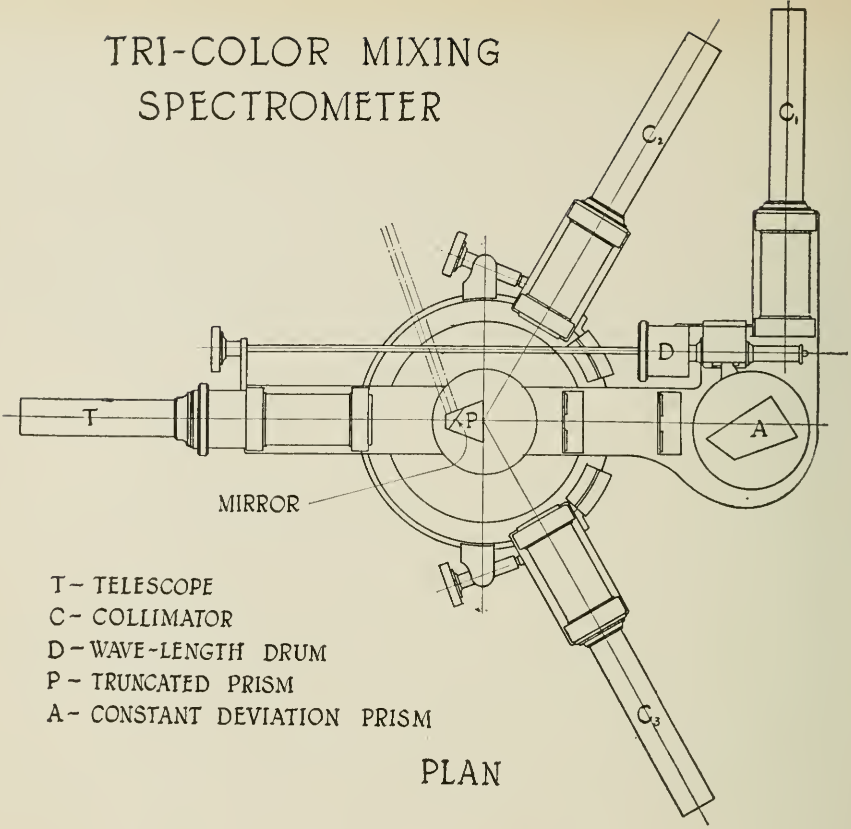
In the Helmholtz color mixing spectrometer the telescope is also fixed in position and the two collimators rotate so as to bring the spectral colors in turn into the telescope. In the figure, the prism, *P*, which in the original instrument of Helmholtz is equilateral, but not truncated, is so placed with reference to the two moveable collimators, C_2 and C_3, that two of the edges are used as refracting angles.

In the new instrument the special prism, *P*, is truncated by a plane accurately parallel to the base. With respect to the spectral rays from the Hilger prism, *A*, the truncated prism acts as a thick plate allowing the light to pass through without deviation and with very little loss by absorption.

The two collimators, C_2 and C_3, rotate, and their spectra can be calibrated in the usual manner by means of verniers and the graduated circle.

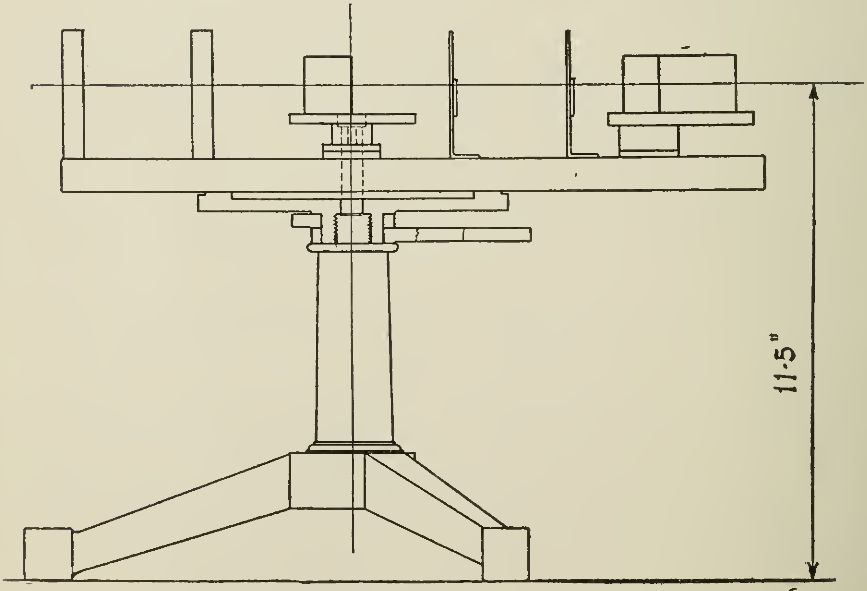
On top of the truncated prism, *P*, which is 1.6 cm high, is mounted a mirror of the same height at such an angle that white or colored light from a side source may be conveniently reflected into the telescope. A total reflection prism might be used instead of the mirror unless the movements of the collimators C_2 or C_3 should interfere with the path of the light.

TRI-COLOR MIXING SPECTROMETER



T – TELESCOPE
C – COLLIMATOR
D – WAVE-LENGTH DRUM
P – TRUNCATED PRISM
A – CONSTANT DEVIATION PRISM

PLAN



SIDE ELEVATION

The slits of the three collimators are provided with special wedges for reducing the apertures so that the three spectra may be placed one above the other; or so that two, or all three of them, may be wholly or partially superposed. The slit widths are controlled and measured by finely graduated micrometer screws. Calibrated neutral tinted wedges may also be used in front of the slits to control and measure the intensities of the light in each spectrum.

When the instrument is properly adjusted the observer can see in the telescope three spectra, one above another, and at the top a rectangular patch of white light reflected from the mirror. As the wedges at the slits are adjustable, the spectra and the white light may be brought into the closest juxtaposition with each other without overlapping. The Hilger shutter eye-piece also enables the observer to control the width of the portions of the spectra in view. Mixtures of two or three spectral colors may be made in any way desired, and the spectral components can be independently controlled and measured both in respect of wave length and intensity.

The spectrum from the collimator C_1 is from a prism equivalent to 60°, and the central ray in the telescope is always at minimum deviation. The spectra from the collimators C_2 and C_3 are formed by refracting angles of about 70°, and the observed rays in the telescope are not at minimum deviation. The last two spectra are identical in dispersion and intensity, though reversed in order of color, while the first differs somewhat from them. The intensities can easily be adjusted to a common standard; the hues, however, may slightly differ.

The spectrometer has not yet been sufficiently used to warrant furthur discussion; but it seems to possess many advantageous features, and any disadvantages or defects will probably be remediable.

The instrument was designed and constructed from sketch plans of the writer by Messrs. Adam Hilger Ltd., London, Eng., with the precision and finish for which that firm is noted.

The writer desires to record his thanks to the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, for a grant covering the cost of this instrument.

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From the PHILOSOPHICAL MAGAZINE, vol. xlvii. *May*, 1924

On the Critical Frequency of Pulsation of Tones. *By* FRANK ALLEN, *Ph.D., Professor of Physics, University of Manitoba, Winnipeg, Canada.*

IN a recent communication with the above title to the Philosophical Magazine †, several relationships were deduced from the experimental data connecting D, the duration of a pulse of sound at the critical frequency of pulsation or flutter of a tone, P, the blowing pressure of the air in the tonvariator, to which the intensity of the sound is proportional, and N, the frequency of vibration of the tone.

The most important of these relationships is that connecting D and P, and was given in the paper:

$$D = K\sqrt{\log P} + C,$$

where K and C are constants.

This equation, applied to the experimental measurements contained in Table II. in the former paper, gave a series of straight lines for different values of N, which were shown in fig. 3, p. 56, in the paper. The lines were so uniformly straight that it was concluded this equation completely satisfied the experimental data.

TABLE.

Pressure P.	log P.	D. N=170.	D. N=180.	D. N=200.	D. N=240.	D. N=264.
		sec.	sec.	sec.	sec.	sec.
2·40 cm.	·380	0·0203	0·0198	0·0189	0·0172	0·0164
2·20 „	·342	·0200	·0196	·0186	·0170	·0160
2·10 „	·322	·0197	·0192	·0183	·0166	·0157
1·98 „	·297	·0194	·0189	·0179	·0162	·0154
1·82 „	·260	·0191	·0186	·0176	·0160	·0151
1·70 „	·230	·0189	·0184	·0173	·0156	·0147
1·62 „	·209	·0186	·0181	·0171	·0153	·0144
1·53 „	·185	·0182	·0177	0167	·0150	·0141
1·45 „	·161	·0177	·0172	·0162	·0143	·0134
1·25 „	·097	·0168	·0163	·0153	·0135	·0126

Reference was also made in the paper to the analogous equation of T. C. Porter, connecting D, the duration of a flash of light at the critical frequency of flicker, and L, the intensity of illumination of a black and white disk,

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† Vol. xlvii. p. 50 (1924).

$$n=\frac{1}{D}=K\log L+C.$$

This equation, when applied to Porter's measurements on white light, was found to have two values for the constant, K, and therefore represented two straight lines with different inclinations, which met at a point representing the low illumination of 0·25 metre-candle.

As this peculiarity of Porter's law has been interpreted as applying to vision by the rods for dim light, and by the cones for bright, there seemed to be no reason why a similar phenomenon should occur in the perception of sound, since nothing suggestive of a double percipient mechanism corresponding to rods and cones exists in the ear.

The authors therefore felt satisfied that the square root of log P was involved in the sound measurements, and did not discover the direct relationship which is here shown to exist.

Recent unpublished work in the writer's laboratory on the sense of touch has brought to light a phenomenon of double action precisely similar to Porter's law in the visual sensation. In consequence of this discovery, the data on sound were re-examined in order to see if Porter's law held there within the range of intensities studied. On plotting the values of D, from Table II. referred to above, and log P, each of the curves was found to consist of two straight lines similar to those found by Porter.

These are shown in the new figure in this paper. Each pair of lines represents observations made on a tone of the frequency indicated, when it was varied from the lowest to the highest available intensity. It may be remarked that Ives[*] found Porter's law to apply to each spectral colour with a suitable change in the constants. This was confirmed by the writer[†].

Table II. of the former paper is given here together with the values of log P instead of the square root of that quantity.

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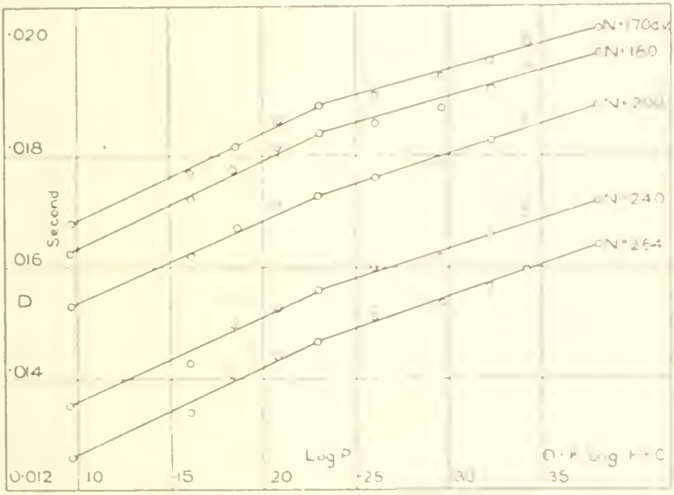
[*] Phil. Mag. vol. xxiv. p. 358 (1912).

[†] Phil. Mag. vol. xxxviii. p. 81 (1919).

The change in slope of the lines in the figure occurs in each case at an intensity given by the tonvariator when blown by an air-pressure of 1·70 cm. of water. This is a quite weak sound, and is comparable with the position of the analogous point found by Porter at the intensity of 0·25 metre-candle.

In the former paper it was pointed out that Porter's law requires the reciprocal of D, whereas in sound D appears directly.



Porter found the angle of inclination made by the upper line representing high intensities to be nearly twice that of the lower. Inserting the numerical values of the constants Porter's law may be written

$$n = 12{\cdot}4 \log L + 10, \text{ for high intensities.}$$

and

$$n = 1{\cdot}56 \log L + 17{\cdot}75, \text{ for low intensities.}$$

The lower branches of the curves for sound in the figure are practically parallel, with a mean angle of inclination of 21° 52′. The upper branches, for more intense sounds, slightly converge, that for N = 170 d.v. having an angle of 15° and the others successively, 16°, 17° 30′, 17° 45′, and 18° 20′. In the analogous case of colours Ives found a similar convergence of the lines.

Porter's equations applied to sound may be written

$$D=0{\cdot}01558 \log P+C, \text{ for low intensities}$$

and

$$D=0.01027 \log P+C, \text{ for high intensities,}$$

where 0·01027 is the mean value of the five constants, which range from 0·00932 to 0·01134.

The values of C vary for the different curves, and apparently are not physiologically significant, unless possibly they may have some connexion with threshold values. It will be noticed also that the larger value of the constant, K, in Porter's equations is for high intensities, whereas the opposite is the case with sounds.

Since Porter's law is derived from Fechner's law *, which is fundamental in sensory nerve action, it ought, therefore, to follow that the fundamental sensory actions and reactions should be similar with all the sense organs. The peculiar alteration of direction of the lines when changing from weak light to strong ought also to be found when changing from any weak sensory impressions to strong. This we now find to be the case with the sensations of sound and touch in addition to that of light.

In light, the Porter effect, as we may conveniently term it, has been referred to the change from rod vision to cone, and therefore has been regarded as confirmatory of the Duplicity Theory of Vision of von Kries. But from the additional evidence adduced here, such an interpretation becomes extremely improbable. The Porter effect appears to be a general property of the sensory nervous system, and hence must be referred to some fundamental property that all such nerves possess in common. The most probable location of the effect appears to the writer to be in the synapses, which Sherrington has found to possess a large number of important functions in nerve conduction.

As it is the intention of the writer to discuss this subject more fully when the experimental data now accumulating are complete, only this addition to, and correction of, the former paper, and its most obvious implications, are noted at present.

On p. 56 of the paper referred to the value ·0311 in Table II. should be ·311, and on p. 57 the word "arbitrary" should be omitted from the last line, as the constants are determined by the nature of the phenomenon and by the mode of experimentation.

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* Peddie, 'Colour Vision,' p. 162.

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Vol. 8, No. 6, June, 1924

ON THE VERIFICATION OF THE PRINCIPLE OF REFLEX VISUAL SENSATIONS

BY

M. S. Hollenberg

ON THE VERIFICATION OF THE PRINCIPLE OF REFLEX VISUAL SENSATIONS[*]

By M. S. Hattwick

SYNOPSIS

Section I. of this communication contains a brief résumé of Allen's work on Reflex Sensations.

Section II. contains descriptions of experiments made by fatiguing the left eye with various colors and then measuring the reflex effects upon the color sensations of the right eye, which is maintained in daylight adaptation.

Section III. contains descriptions of the fatigue and reflex effects of color stimuli when applied to the right eye, the left being maintained in daylight adaptation. The direct and reflex effects of white light and darkness are also studied.

Section IV. contains theoretical discussions relative to some of Burch's experiments on fatigue, and to the brief initial over-shooting of sensation when a stimulus is first applied to the eye. The experimental results are shown to support the fundamental theory of Young and Helmholtz.

I.

The recent investigations[1] by Allen on the effects of retinal fatigue upon color sensations has led to the discovery of a new physiological reflex which is sensory in its nature. The rôle of this sensory reflex opens a new field in color vision as well as in the physiology of receptor end-organs.

Allen's work indicates that when light falls upon any part of either retina, the perception of the three fundamental color sensations, red, green, and violet, as measured by the critical frequency of flicker, is enhanced in both retinas. The experiments to be described in this communication were undertaken to ascertain if the results obtained by Allen applied to another normal individual. This was found to be the case. The writer investigated practically the whole of the spectrum and found that in every instance his curves were identical with those of Allen.

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[*] Read at the meeting of The Optical Society of America, Cleveland, O., October, 1923.

[1] On Reflex Visual Sensations, J. O. S. A. and R. S. I. 7, p. 583, 1923. On Reflex Visual Sensations and Color Contrast, ibid. p. 913.

The apparatus used to determine the critical frequency of flicker was arranged as follows:- Light from an acetylene flame passed through a rotating disk with two opposite open sectors of 90° each. The flickering light so produced, entered a spectrometer and was viewed as a spectrum in an eye-piece with adjustable shutters, which cut off all the spectrum except a narrow rectangular band of the desired wave length. By electrical means the speed of the disk was recorded when the flickering of the light in the eye-piece was perceived as a just continuous sensation. The duration in time of the light impulses which is required to produce a continuous sensation varies with the luminosity or physiological brightness of the spectrum; and when plotted with the wave lengths of the colors observed as abscissae, a curve is obtained called the persistency curve. The time on any point of this curve is referred to as the critical frequency of flicker for the corresponding wave length.

By this means a normal curve was obtained for the right eye which served as a standard of comparison for other persistency curves taken under varying conditions which will be discussed. This normal curve was checked throughout the investigation and was found to remain constant.

In fatiguing the eye a second spectrometer was used with the electric arc as the source of light. An eye-piece with adjustable shutters isolated the wave lengths with which the eye was fatigued.

It is important to note that this work was carried out in a room illuminated by diffused daylight.

The reflex curves were obtained by keeping the left eye in a state of fatigue with the particular wave length whose effect was to be investigated, and measuring the critical frequency of flicker with the right eye for which the normal had been definitely established. Between readings the right eye was kept in constant daylight adaptation.

The fatigue curves were determined by fatiguing the right eye with the desired wave length, and ascertaining the persistency curve with it, the left being always maintained in daylight adaptation.

It is thus clear that all the persistency curves to be shown were obtained with the right eye of the observer.

In each figure two curves are plotted; the normal curve for the right eye is shown as a broken line, and the reflex or fatigue curve is shown as a continuous line. At the bottom of each figure the same curves are reproduced in another form by making the normal curve a straight line and giving it an arbitrary value of 100, and reducing the fatigue and reflex curves in the same proportion. The wave length of the fatiguing color is indicated by a short vertical line in each figure.

II. REFLEX CURVES

First to be considered are the reflex curves, that is the curves obtained by the right eye when the left was fatigued by a definite wave length. The persistency curves given were selected to represent the whole spectrum. The data of all the curves discussed in this section are given in Table 1.

The effect produced upon the right eye by preventing all stimulation of the left by blindfolding it, was first obtained. The curves in Fig. 1 show that by removing all stimulation of the left eye, the retina of the right eye reacts more sluggishly than normal with the result that the persistency curve lies wholly above the normal with the same physical spectrum, indicating that its physiological brightness is reduced below its normal value. It is evident that the right eye is rendered less sensitive to the whole spectrum by removing the stimulation produced upon the left eye by diffused daylight.

Conversely, when the left eye is stimulated by white light more intense than diffused daylight, e.g. white light from the arc, which was used in this experiment, the right eye, as shown by the persistency curves in Fig. 2, becomes much more sensitive to every color of the spectrum, and there is in consequence depression of the whole curve below the normal. In both figures, 1, and 2, the reduced curves show a marked threefold division corresponding to the colors red, green-yellow and violet.

In the next experiment the left eye was fatigued with red light of wave length .687μ. The curve for the right eye in Fig. 3 is characterized by three depressions below the normal, which are better shown in the reduced curves at the bottom of the figure. These occur in the regions corresponding to the red, green, and violet colors. The depressions are not confined to these colors but extend into the surrounding regions

TABLE 1. *Reflex Curves*

λ	Normal sec.	White Light sec.	Darkness sec.	.687μ sec.	.660μ sec.	.589μ sec.	.572μ sec.	.540μ sec.	.450μ sec.	.410μ sec
.74μ	0.0340	0.0308	0.0400	0.0315	0.0333	0.0316	0.0338	0.0326	0.0324	0.0324
.72	.0282	.0265	.0305	.0266	.0281	.0264	.0280	.0268	.0265	0266
.70	.0240	.0228	.0260	.0226	.0240	.0224	.0237	.0226	.0224	.0228
.68	.0202	.0189	.0219	.0190	.0205	.0195	.0201	.0194	.0194	.0192
.66	.0172	.0166	.0191	.0163	.0175	.0164	.0170	.0166	.0164	.0167
.64	.0160	.0152	.0172	.0157	.0163	.0149	.0157	.0156	.0157	.0161
.62	.0151	.0142	.0168	.0142	.0153	.0137	.0148	.0147	.0145	.0146
.59	.0148	.0137	.0163	.0139	.0151	.0131	.0145	.0140	.0142	.0139
.55	.0155	.0143	.0166	.0147	.0153	.0141	.0152	.0148	.0148	.0149
.53	.0166	.0154	.0173	.0155	.0164	.0151	.0164	.0151	.0152	.0161
.50	.0210	.0200	.0216	.0201	.0205	.0204	.0210	.0207	.0207	.0201
.48	.0255	.0240	.0289	.0244	.0252	.0243	.0254	.0249	.0248	.0240
.46	.0310	.0279	.0335	.0293	.0310	.0304	.0309	.0301	.0303	.0295
.44	.0350	.0326	.0415	.0342	.0343	.0332	.0349	.0337	.0342	.0322
.42	.0420	.0402	.0507	.0401	.0410	.0401	.0414	.0400	.0401	.0382

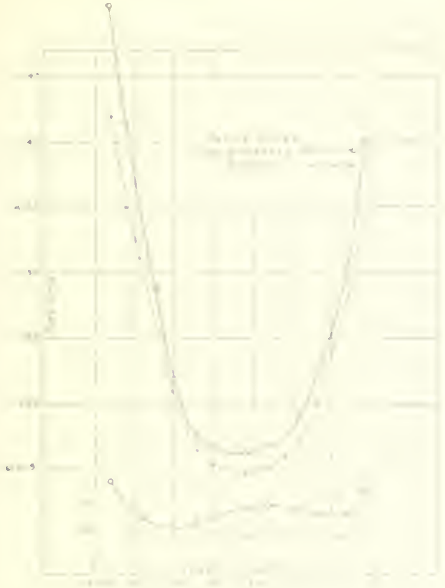

FIG. 1.
Reflex Curve for Daylight.

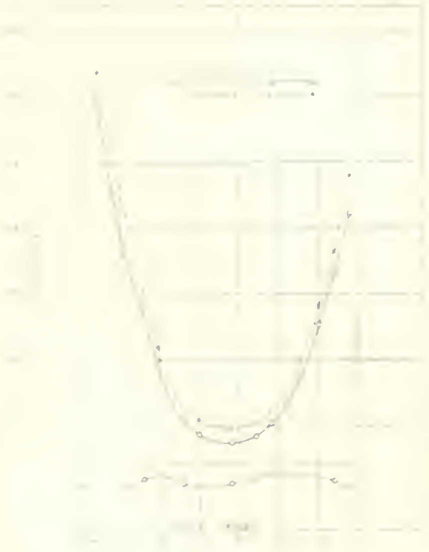

FIG. 2.
Reflex Curve for White Light.

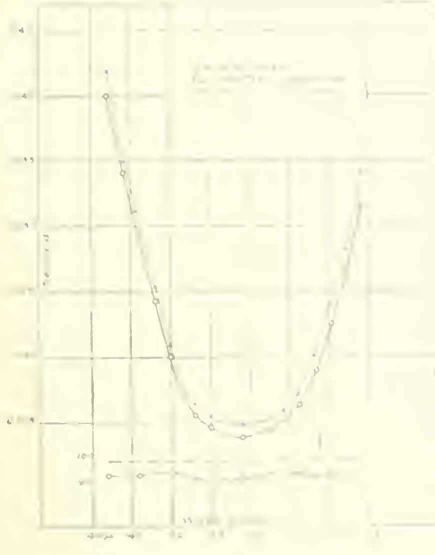

FIG. 3.
Reflex Curve for .467μ.

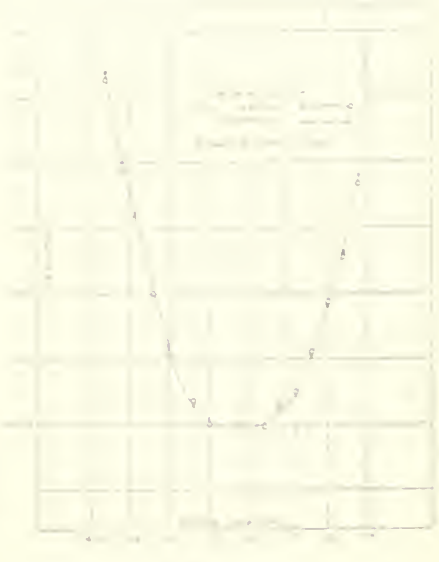

FIG. 4.
Reflex Curve for .560μ.

as well. The conclusion to be drawn is that by a sensory reflex process the effect of fatiguing the left eye with red light of wave length .687μ, was transferred to the right eye, and there resulted in an enhancement of the brightness of three spectral regions. The three depressions are separated by two points at about .64μ and .52μ where the normal and abnormal curves approximate each other. The curves obtained when the wave lengths .660μ and .572μ were employed as fatiguing stimuli are shown in Fig. 4 and Fig. 6, respectively. They have no depressions, but coincide with the normal curve throughout their length. Allen[2] has named these wave lengths equilibrium colors. In the paper just cited Allen found the second equilibrium color at .570μ, but subsequently[3] he determined it more exactly at .572μ.

In Fig. 5 is shown the reflex effect of the yellow color .589μ. This is about the brightest part of the spectrum and gave the greatest reflex effect obtained, i.e. the greatest enhancement of the red, green, and violet sensations. The three depressions in this curve are well marked and the coincidence or division points are at the wave lengths .50μ and .67μ.

In Figs. 7, 8, and 9 are shown the reflexes obtained with the fatiguing colors .540μ, .450μ, and .410μ, respectively. All these curves, like the above, exhibit the usual three depressions, indicating enhancement of the three color sensations.

From a consideration of the above curves, it is evident that stimulation of the left eye by any color has but one effect upon the retina of the right eye, viz., the latter is so altered that the sensitiveness of the three fundamental color sensations is increased. The equilibrium colors are exceptions to this statement; for fatiguing the left eye with these produces no effect upon the right eye.

One striking feature especially noticeable is that while the luminosity of violet of wave length .410μ is about one seven-hundredth of that of yellow .589μ, the depressions produced by the latter color are but slightly greater. This shows that the magnitude of the reflex effect is not a direct function of the physiological brightness of the stimulus.

Only two of the equilibrium colors, .660μ and .572μ were verified. The remaining four found by Allen[4] at the wave lengths .520μ, .505μ, .480μ, and .425μ, were not tried, as the general verification of his results was so complete.

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[2] On Reflex Visual Sensations, Loc. cit., p. 610.

[3] Reflex Visual Sensations and Color Contrast. J. O. S. A. and R. S. I. 7, p. 921; 1923.

[4] J. O. S. A. and R. S. I., 7, p. 611; 1923.

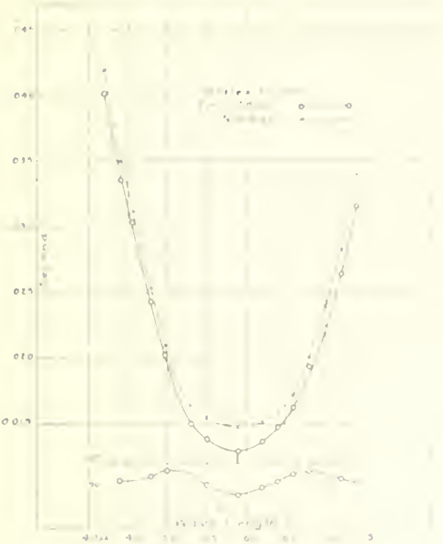

Fig. 5

Reflex Curve for 500μ

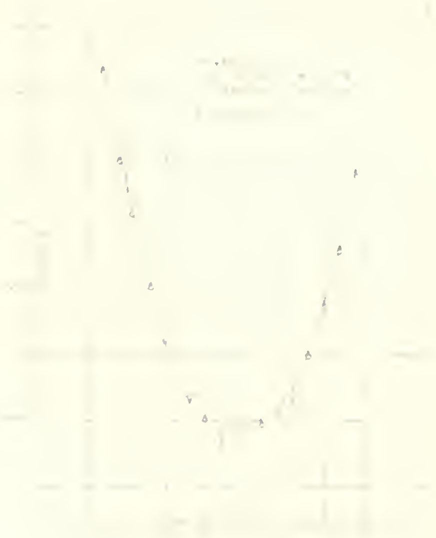

Fig. 6

Reflex Curve for 520μ

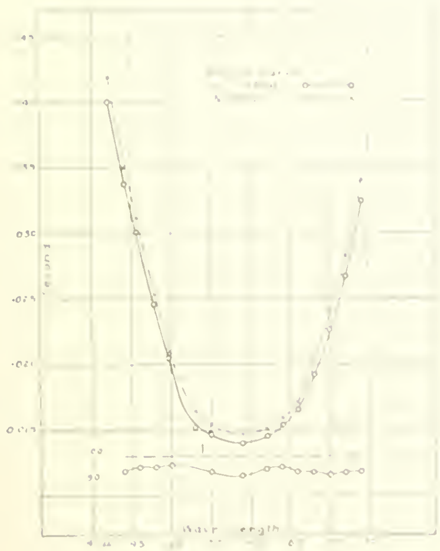

Fig. 7

Reflex Curve for 540μ

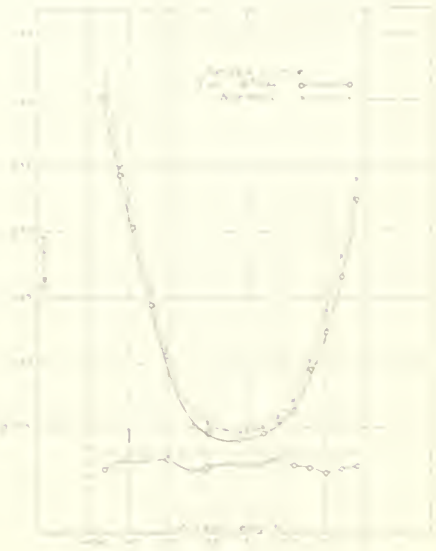

Fig. 8

Reflex Curve for [illegible]

It will be noticed in the preceding curves that while fatigue of one eye always reflexly enhances the perception of the spectrum in the other in the three regions red, green, and violet, the predominant enhancement is in the sensations complementary to the color used for fatigue.

In connection with these reflex effects some observations by Edridge-Green[5] are of interest. "When one eye is fatigued with a spectral colour, the other eye being kept closed and covered with the hand, and then the eye which has been fatigued is closed and a white surface viewed with the unfatigued eye, this appears as if it were mixed with the colour of the light used which was fatiguing the other eye."

In these observations of Edridge-Green the reflex effects of fatigue transferred from one eye to the other were complicated by darkness adaptation which affects the different sensations unequally, as may be seen by examining the curves in Figs. 1 and 10.

Edridge-Green also directs attention to the possibility of error arising from comparing observations made simultaneously by a fatigued eye and by the other which is assumed, often erroneously, to remain in its normal condition.

The presence of these reflex effects in the unfatigued eye may possibly invalidate some of the observations of Burch in his experiments on fatigue. In one of his papers[6] he thus describes his method of making observations: "I then exposed my eye for a few seconds to the extremely bright light in the focus of the lens, and immediately afterwards looked through a single-prism spectroscope illuminated by the light of the sky, comparing the results with those given by the other eye, which had not been exposed to the light."

Darkness adaptation of and reflex effects in the unexposed eye may easily have altered the appearance of colors which was assumed by Burch to remain quite normal.

III. FATIGUE CURVES

We shall now consider the fatigue curves, or the persistency curves obtained by the right eye when it was fatigued by colors of definite wave lengths. The data for all the curves in this section are given in Table 2.

As in the reflex curves, it was decided first to ascertain the effect of darkness adaptation of the observing eye. This condition was pro-

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[5] New Researches in Colour Vision, Lancet, p. 360; 1922.

[6] On Artificial Temporary Colour Blindness. Phil. Trans. B., *191*, p. 4; 1899.

TABLE 2. *Fatigue Curves*

λ	Normal sec.	White Light sec.	Darkness sec.	.687μ sec.	.660μ sec.	.589μ sec.	.572μ sec.	.540μ sec.	.450μ sec.	.410μ sec.
.74μ	0.0340	0.0390	0.0357	0.0361	0.0335	0.0355	0.0341	0.0306	0.0321	0.0320
.72	.0282	.0325	.0300	.0302	.0282	.0301	.0283	.0257	.0266	.0269
.70	.0210	.0280	.0258	.0251	.0240	.0258	.0242	.0229	.0235	.0227
.68	.0202	.0232	.0216	.0209	.0205	.0210	.0201	.0191	.0205	.0191
.66	.0172	.0209	.0187	.0171	.0174	.0176	.0171	.0168	.0177	.0169
.64	.0160	.0180	.0171	.0155	.0159	.0167	.0160	.0157	.0165	.0152
.62	.0151	.0167	.0163	.0143	.0154	.0160	.0150	.0150	.0157	.0145
.59	.0148	.0160	.0159	.0138	.0150	.0159	.0136	.0148	.0150	.0145
.55	.0155	.0171	.0171	.0148	.0154	.0173	.0154	.0171	.0160	.0148
.53	.0166	.0179	.0190	.0160	.0185	.0184	.0163	.0181	.0189	.0157
.50	.0210	.0231	.0237	.0210	.0205	.0201	.0209	.0209	.0222	.0210
.48	.0255	.0276	.0275	.0250	.0252	.0241	.0238	.0281	.0265	.0260
.46	.0310	.0356	.0341	.0298	.0309	.0301	.0310	.0286	.0328	.0340
.44	.0350	.0388	.0387	.0339	.0342	.0352	.0347	.0326	.0377	.0370
.42	.0420	.0458	.0451	.0404	.0409	.0401	.0419	.0393	.0481	.0435

duced by blind-folding the right eye and removing the eye shield only while a reading in the spectroscope was being taken. The left eye was in normal daylight adaptation, which was the case with all curves described in this section. From the curve in Fig. 10 we see that the absence of all stimulation from the right eye elevates the whole persistency curve above the normal, indicating that the physiological brightness of the spectrum is diminished, and that the sensitiveness of the retina for all color impressions is depressed.

If this curve be compared with that in Fig. 1 for the apparent reflex effect of darkness adaptation of the left eye, the two will be observed to be similarly elevated above the normal. The direct effect of darkness adaptation of the retina, and the transferred effect of darkness adaptation of the other retina, operate in both cases to depress the sensitiveness of both retinas to all colors.

The converse of this experiment was now tried by subjecting the retina to white light of great intensity from an arc lamp. The curve obtained by the right eye, Fig. 11, was again above the normal in all parts, indicating fatigue of all three sensations.

It is to be observed that the effects of darkness and bright white light upon the observing eye are almost identical. Thus we see that the eye is best adapted for the perception of color stimuli in diffused daylight; and that its power of perception is depressed either by very strong stimulation or by the absence of stimulation, i.e. by darkness.

The curve obtained by fatiguing the observing eye with red light of wave length .687μ is shown in Fig. 12. The effect produced is an elevation or fatigue effect in the part corresponding to red; and two depressions below the normal indicating reflex enhancement of perception in the violet and green. The two points which almost correspond to the normal are found as before at the wave lengths .66μ and .50μ.

The right eye was fatigued in turn with the equilibrium colors .660μ and .572μ. The curves coincided with the normal like those shown above in Figs. 4 and 6. This indicates that fatigue with equilibrium colors produces neither depression nor enhancement of the color sensations. At these points the direct and reflex effects of the color stimulus balance each other with the result that the normal physiological brightness of the spectrum is undisturbed.

The color between these two equilibrium points selected for the fatiguing stimulus was the wave length .589μ. The resulting persistency

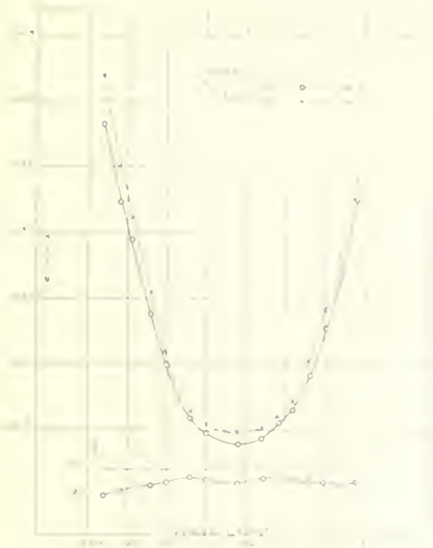

Fig. 9

[illegible]

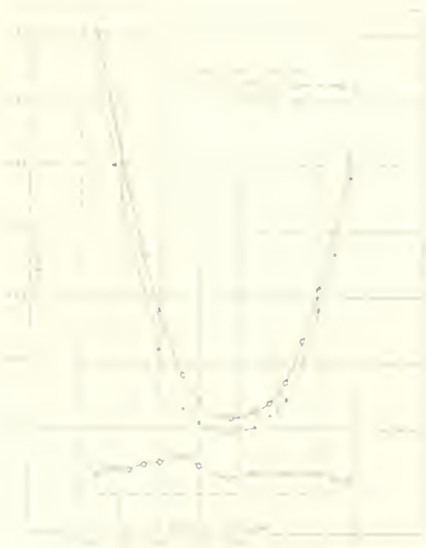

Fig. 10

[illegible]

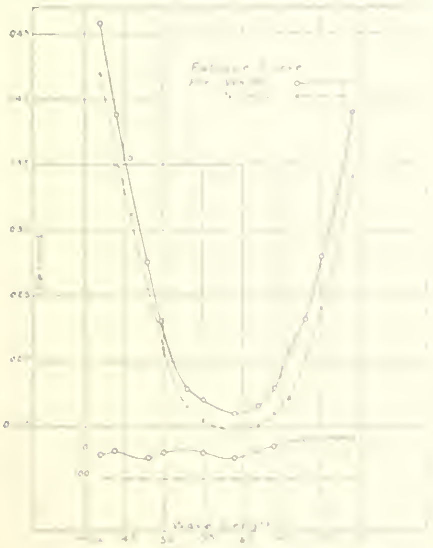

Fig. 11

[illegible]

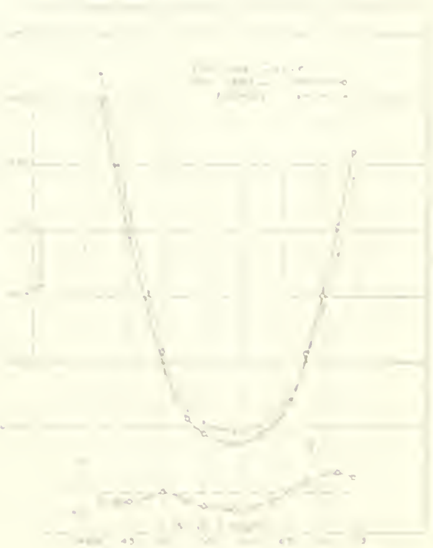

Fig. 12

[illegible]

curve, in Fig. 13, is characterized by two prominent elevations in the red and green, and a depression in the violet, separated from each other by the wave lengths .50μ and .66μ. The two elevations prove that yellow light directly affects the red and green sensations, and reflexly the violet. Yellow is thus seen to be compound in its nature.

The next color used for fatigue was green of wave length .540μ. The effect produced by this color, as shown in Fig. 14, is a fatigue elevation in the part corresponding to green, and reflex depressions in those corresponding to red and violet. The three parts are separated by the wave lengths .50μ and .66μ as before. Green, like red, is a simple sensation and therefore fatigues only one part of the spectrum.

The effect produced by blue of wave length .450μ is shown in Fig. 15. Two fatigue elevations are caused in the green and violet regions of the curve, and a reflex depression in the part corresponding to red. Blue, like yellow, is therefore shown to be compound in its nature.

The last color tried was violet of wave length .410μ. The curve in Fig. 16 is characterized by a fatigue elevation in the part corresponding to violet, and two reflex depressions in the parts corresponding to green and red, which are separated at the wave lengths .50μ and .66μ. As in the case of red and green, the single elevation shows violet to be a primary or fundamental sensation.

In measuring the critical frequency of flicker in the right eye when it was fatigued by very bright white light, observations were also made by slight indirect vision upon an adjoining area of the retina. The measurements, in Table 3, are shown graphically in Fig. 17. The curve is below the normal in all parts, showing that upon the retinal area employed, the fatiguing white light has a sensory reflex effect precisely the same as was found by transference from one eye to the other, as shown in Fig. 2. This proves that fatigue upon one area of a retina enhances color vision in adjoining areas by reflex action. The curve therefore confirms Allen's[7] results by which he explained the phenomena of contrast.

IV. THEORETICAL CONSIDERATIONS

In the first series of reflex curves, stimulation was confined to the left eye, and the reflex effect, which occurred in both eyes, was isolated in the right. We are justified therefore in concluding that every ray of light excites in the visual apparatus reciprocal or reflex effects which

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[7] Reflex Visual Sensations and Color Contrast. J. O. S. A. and R. S. I., 7, p. 929, 1923.

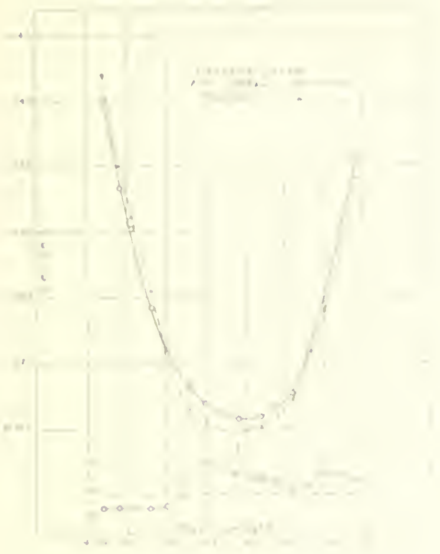

Fig. 13

Fatigue Curve for [illegible]

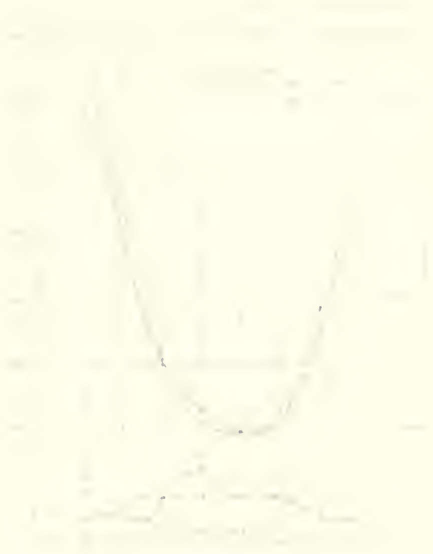

Fig. 14

Fatigue Curve for [illegible]

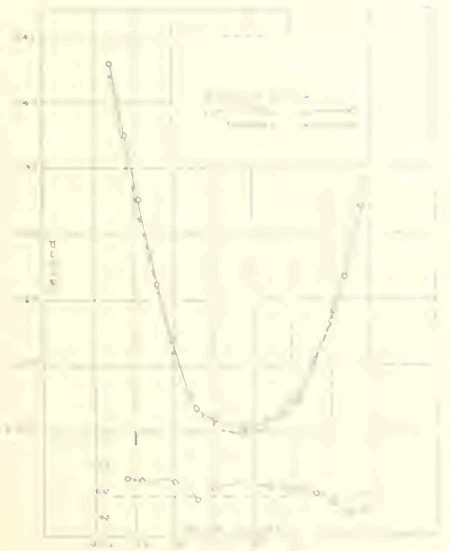

Fig. 15

Fatigue Curve for [illegible]

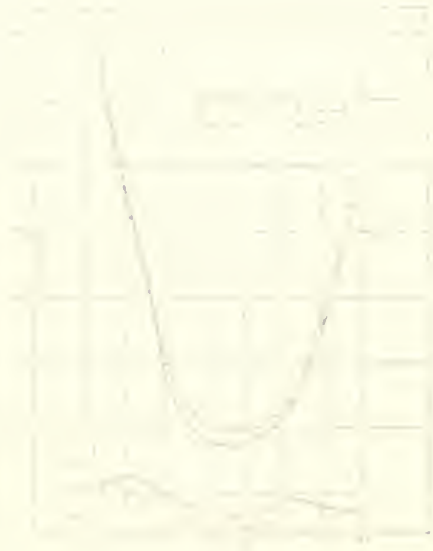

Fig. 16

Fatigue Curve for [illegible]

enhance the physiological brightness of the three parts of the spectrum, red, green, and violet.

In the second series of fatigue curves, the elevations are the algebraic sums or the net results, of fatigue and reflex action, the balance being in favor of fatigue in the sensation or sensations directly affected.

TABLE 3. REFLEX CURVE FOR WHITE LIGHT

λ	Normal	White Light	λ	Normal	White Light
	SEC.	SEC.		SEC.	SEC.
.74μ	0.0340	0.0331	.55μ	0.0155	0.0145
.72	.0282	.0275	.53	.0166	.0157
.70	.0240	.0233	.50	.0210	.0204
.68	.0202	.0194	.48	.0255	.0248
.66	.0172	.0165	.46	.0310	.0300
.64	.0160	.0151	.44	.0350	.0343
.62	.0151	.0144	.42	.0420	.0409
.59	.0148	.0140			

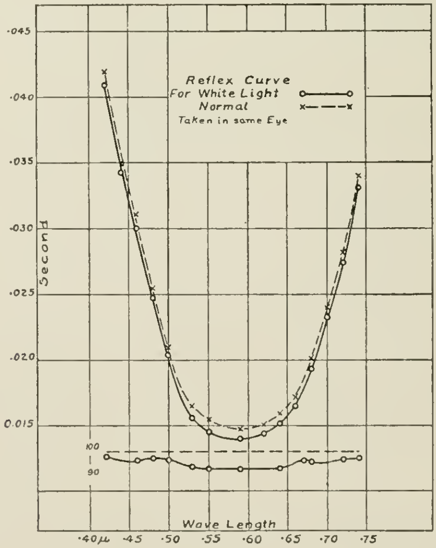

FIG. 17

Reflex Curve for White Light on Area adjoining fatigued Area.

The depressions indicate the parts of the spectrum reflexly enhanced. In both sets of curves the predominant enhancement occurs in the sensations complementary to the fatiguing color.

With this conclusion some of Burch's experiments on fatigue agree. Hartridge[8] refers briefly to these by saying that Burch found the complementary color actually to appear more vivid than usual after fatigue with any color.

In the paper by Burch, to which reference has been made above[9] he mentions certain observations made in his flower garden after fatiguing his eye with excessively bright colors from sunlight. Only one observation is quoted here.

"During the condition of purple-blindness all red, purple, or blue flowers look nearly black, but the grass appears of a brilliant rich green beside which its color to the normal eye is dirty by comparison." It will be remembered that purple is the complementary of green.

Afterward in continuing his experiments on spectral colors in his laboratory, Burch concludes that "the temporary abolition of any one color sensation is without effect on the intensity of the remaining color sensations, neither increasing nor diminishing them unless they have been to some extent implicated in the light used for producing color blindness."

In the first experiments Burch was in his garden in bright daylight while his eye was being fatigued; in the second he was in his dark laboratory. In daylight he found the complementary of the fatiguing color to be enhanced in brightness as the quotation on the effect of purple-blindness, for example, plainly shows. In the dark laboratory, on the contrary, the complementary color was unaffected.

The first observations conform to the experimental results discussed in this paper. Allen[10] has shown that the transferrable effect of darkness adaptation from one eye to the other balances and thereby conceals the reflex enhancement of the complementary of the fatiguing color, a result which explains the negative conclusions of Burch from his second experiments.

In Bidwell's experiment,[11] by which he showed that a red color, viewed intermittently by rotating a white and black sectored disk, loses its original hue and appears green, we have a vivid example of the visibility of the reflex enhancement of the complementary color. The speed of rotation necessary to produce this effect shows that the flash of red light stimulates the eye for from 0.015 sec. to 0.02 sec., which is about the same interval of time as that of the most rapid motor reflex.

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[8] In Starling's "Human Physiology," 3rd Ed., p. 571.

[9] See also, Parson's "Colour Vision," p. 113.

[10] On Reflex Visual Sensations, loc. cit. p. 607.

[11] Proc. Roy. Soc., 61, p. 269, 1896. Also Allen, F., Reflex Visual Sensations, loc. cit., p. 619.

But before the enhancement of the green sensation occurs, the red itself becomes much brighter, as Bidwell observed. This can only be interpreted as the reflex enhancement of the red sensation which takes place in a shorter interval of time than the enhancement of the green under the influence of red light.

This effect has been studied, among others, by Broca and Sulzer,[12] who found that when a color of constant intensity falls on the retina the sensation which it produces does not attain its permanent value immediately, but rises rapidly to an intensity much greater than the normal to which it then similarly falls. In the case of red the overshooting of brightness, as it has been called, causes that color to appear about twice its normal brightness, green a little brighter than normal, and blue about five times its normal intensity. The amount of overshooting depends upon the luminosity of the stimulus.

The curves obtained by Broca and Sulzer for red, green, and blue, are reproduced in Fig. 18. The numbers on the curves, and the dotted horizontal lines on the right side of the figures, indicate the final steady values of the colors employed.

From these it is seen that for a very short interval of time the stimulus is unable to produce a sensation of brightness equal to the normal value. The intensity curve makes a sharp bend upward until the normal value is reached when it 'overshoots' rapidly. These characteristics are shown in the curves for all three colors.

In the case of the curve for blue, the first inflection, which probably marks the beginning of the reflex enhancement, occurs in 0.0156 sec., which is about the value Bidwell found for the development of the green reflex with a red stimulus. The sensory reflex effect, as we have shown, enhances the perception of color, and since it makes its appearance in the time estimated for the reflex to occur, it is practically certain that the overshooting in all cases is due to the initial and almost unopposed reflex enhancement of the sensations.

Now the reflex enhancement is probably of a constant value, but the direct fatigue progresses with the time of stimulation. The result is that up to 0.054 sec., in the case of blue light, the reflex enhancement preponderates over the direct fatigue, and after that the direct fatigue increases above the reflex effect, and the physiological brightness gradually decreases. In 0.25 sec. (blue) it reaches its normal value; that is, the reflex and direct effects maintain a definite ratio towards each other.

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[12] Comp. Rend., *2*, p. 1046; 1903. Also Luckiesh, Color and its Applications, p. 139.

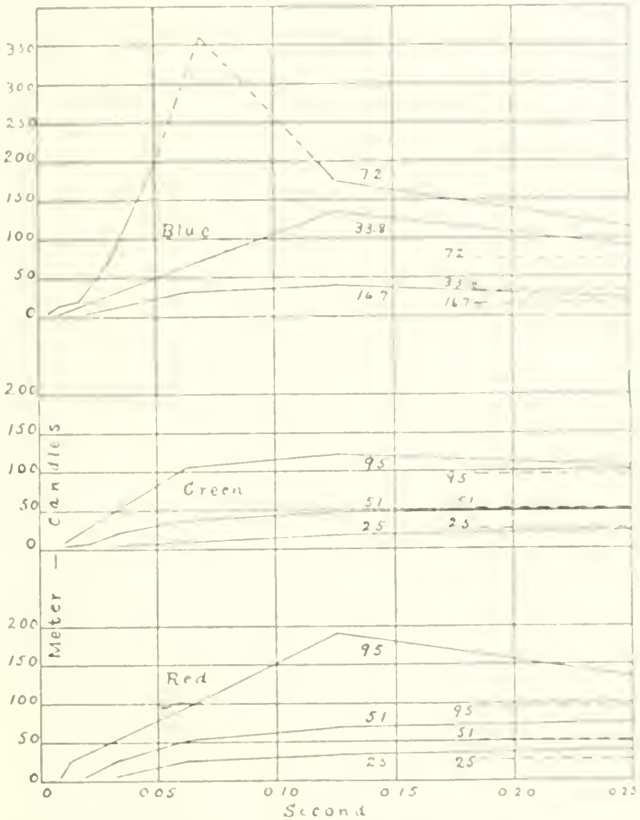

Fig. 10

Curves showing initial development of red, green, and blue sensations. (Broca and Sulzer.)

The curves also show that when the stimulus is sufficiently diminished in intensity, probably at some critical value for each color, the opposing or antagonistic direct and reflex effects, i.e., fatigue and enhancement, progress together in such a manner that the normal brightness is approached without overshooting.

The result of this application of the reflex theory is twofold: first, Broca and Sulzer's curves corroborate the reflex time as computed from Bidwell's effect; second, it affords an explanation of the overshooting of sensations which hitherto has been lacking.

The results discussed in this communication are experimental and therefore quite independent of any theory. The uniform threefold character of the elevations and depressions in the curves confirms the trichromatic nature of color vision. The color theory of Young and Helmholtz, when enlarged by the addition of Allen's principle of the reflex enhancement of sensations or the sensory reflex, is quite in harmony with the facts disclosed by the curves.

This communication forms part of a series of investigations relating to Color Vision and the physiology of the receptor end-organs now in progress in the Department of Physics of the University of Manitoba, under the direction of Professor Frank Allen, and with the financial assistance of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa.

I desire to express my thanks to Professor Allen for the use of his apparatus and for his suggestions in connection with the work.

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REFLEX VISUAL SENSATIONS AND ANOMALOUS TRICHROMATISM

BY

W. A. ANDERSON

REFLEX VISUAL [illegible]
[illegible]

[illegible]

[illegible]

Sec. I. Introduction. [illegible] sensations [illegible] to determine the [illegible]

Sec. II. Apparatus and [illegible] a daylight [illegible] quantitative [illegible]

Sec. III. Normal Curve [illegible] curve, taken [illegible] found to be the same for [illegible] red color blindness.

Sec. IV. Reflex Curves.—[illegible] carried out by [illegible] response of the [illegible]

The nature of [illegible] brightness of the [illegible] reflex enhancement [illegible] .520μ to .480μ [illegible] greatest [illegible] also transferred [illegible]

Sec. V. Fatigue Curves. [illegible] the measurements [illegible] tation

It was found [illegible] enhancement. [illegible] position. No effect [illegible] effect for .520μ. [illegible] fatigue characteristics.

Sec. VI. The Trichromatic Considerations.—[illegible] of light produces [illegible] are shown to be red, green, [illegible] an anomalous trichromatic [illegible] the phenomena as well as [illegible] Young Helmholtz [illegible] theories, but can be harmonized [illegible]

I. Introduction

In recent investigations by Allen[1] abundant experimental evidence has been brought forth establishing a new principle in color vision, the application of which to the Young Helmholtz theory [illegible] simple and satisfactory explanations of many of the phenomena of color perception.

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[1] J. O. S. A. & R. S. I., 7, p. [illegible]

which were admittedly inexplicable on the basis of the trichromatic theory.

His results show that the effect of fatiguing a given area of one retina with any spectral color, except an equilibrium one, is to lower the luminous response of that area to colors corresponding to the sensations directly affected by the fatiguing stimulus, and to enhance its response to colors exciting chiefly the complementary sensations. However, when the colors are received upon a portion of the retina adjoining the fatigued area,[2] or by the retina of the other eye, the physiological luminosity of the entire spectrum is enhanced. Thus the conclusion is drawn, that every ray of light produces two effects, a direct and a reflex. In the stimulated area of the retina, the direct action fatigues either one or two of the fundamental sensations, according as the color stimulus is simple or compound in its nature; the reflex effect enhances the luminous response of the remaining complementary sensations. It is further concluded that the reflex is transferred to the adjoining areas of the same retina, and also to the other eye, in such a way as to enhance all three sensations.

The author of this paper set out to repeat some of these observations but immediately discovered, from the character of his normal persistency curve, that his perception of light and color is somewhat abnormal. It was therefore of interest to determine the character of these direct and reflex actions of light for one of abnormal vision.

II. Apparatus and Methods of Observation

The apparatus used and the method adopted was, in most respects, the same as that employed by Allen. For the purpose of measurement the apparatus was essentially the same as that originally devised by E. L. Nichols.[3] The source of light was an acetylene flame, for which the gas was supplied at a constant pressure. The light was focused upon the slit of the collimator of a Hilger spectrometer, fitted with four prisms equivalent to three of sixty degrees each. This gave a spectrum of considerable dispersion, narrow strips of which could be isolated in a shutter eyepiece. Between the acetylene flame and the condensing lens an aluminum disk with two opposite open sectors of ninety degrees each was rotated. The speed of rotation, which was regulated by means of a brake, was electrically recorded upon a chronograph. The gas flame was enclosed on all sides, except the top, in a wooden box fitted with a small glass window which transmitted the light to the spectrometer. This box served two purposes: first, in preventing the air currents, produced by the rotating disk, from affecting the flame; and second, in shielding the light from the observer's eyes. The spectrometer was properly screened from all extraneous light, and a shield, closely fitting about the eye, was attached to the eyepiece, thus enabling all measurements to be made under exactly the same conditions.

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[2] J. O. S. A. & R. S. I., 7, p. 913; 1923.

[3] E. L. Nichols, Am. Jour. Sci., *28*; 1884.

The spectrum used for fatiguing the eye, in the case of nearly all the reflex and also for some of the fatigue curves, was obtained from an arc light by means of a two-prism Browning spectrometer. A narrow but quite long rectangular patch of the spectrum was isolated by the shutter eyepiece. The spectrum was so intense that the colors in the middle portions of it approached whiteness in appearance. For the majority of the fatigue curves a constant deviation Hilger spectrometer was employed to furnish the fatiguing color. With this instrument the source of light for the blue and violet was always the electric arc, and for the remainder of the fatiguing colors, sometimes the arc was used, and at other times an incandescent bulb, which produced a red of about the same intensity as that of the arc spectrum. The use of the Hilger spectrometer and incandescent bulb made a more convenient arrangement of the apparatus, enabling measurements to be made within a few seconds after removing the eye from the fatiguing color.

While fatiguing one eye, or making measurements, which was always done with the right, the unused eye was directed at a neutral grey surface about ten inches away. Sometimes, when recording observations on the dim ends of the spectrum, the left eye was closed for a few seconds, which did not exceed half a minute. No difference could be detected in the time of the critical frequency of flicker, as recorded for the brighter parts of the spectrum when the left eye was closed for a few seconds, and it was assumed that the time was unaffected for the dim colors.

All the apparatus was mounted in a room well illuminated with daylight. Measurements were not attempted if it was too cloudy or dull or towards sunset, and never with artificial lighting, for Allen has shown that dim light and darkness tend to obscure the reflex action of light.

The rotating sectored disk produced a flickering sensation in the isolated patch of the spectrum, due to the rapid succession of equal intervals of color and darkness. After adjusting the speed of the motor until the flicker was just imperceptible, the chronograph was started, and while the record was being made, which required about half a minute, the speed of the disk was varied slightly, keeping the flicker just on the point of appearing and disappearing. At least two independent records, representing the time of 120 and 400 revolutions of the disk, were made for each point, and if these did not show good agreement more readings were taken. So constant were the conditions, that the independent records gave values for the duration of a single flash, at the critical frequency of flicker, with a variation seldom greater than 0.0002 sec., except for points in the dim ends of the spectrum. The values used in plotting points in the bright parts of the spectrum were means of usually two or three independent measurements, and for the extreme violet and red the mean of about four readings was taken.

These experiments stretched over an interval of about fifteen months, most of the work being done, however, during the first three and the last five months. The curves were not necessarily taken in the order presented in this paper, although nearly all of the reflex curves were completed during the first three months and before any fatigue curves were attempted.

III. NORMAL CURVES

In making measurements for a normal curve, the following procedure was adopted. The spectrometer was set so that the shutter eyepiece isolated a narrow rectangular patch of the spectrum, the mean wave length of which was known. The spectral color was observed by the right eye, while the speed of the disk was regulated to give the critical frequency, which was then recorded. Care was taken to fixate the color directly, and to prevent the eye from wandering while judging the point of critical frequency. The eye was then rested for a minute or two, and a second chronographic record made on the same portion of the spectrum. Between the measurements made on different points in the spectrum the eye was rested in the diffuse daylight of the room for from five to ten minutes, according to the brightness of the spectral color. Since the spectrum, upon which all measurements were made, was not very brilliant, and the time required to record one reading about half a minute, the eye was not likely to become appreciably fatigued. In this way, observations were made on fifteen or more points of the spectrum.

The persistency curves, obtained by plotting wave lengths as abscissae and the persistence of vision as ordinates, show that the duration of these light impulses varies as some inverse function of the luminosity of the color observed. It was discovered by Ferry[4] and subsequently in another manner by Porter[5] that the duration of the sensation of undiminished brightness of a flash of light at the critical frequency of flicker, depends only on the luminosity of the light and in no way on the wave length. The Ferry-Porter law, as it is known, is represented by the equation, $D = \frac{1}{k \log L + k_0}$ where D is the persistence of vision, L the luminosity, and k and k_0 two constants. According to this law, a lowering of the persistency curve may be interpreted as an increase and an elevation as a decrease in the luminosity of the spectrum as perceived by the eye.

Considerable difficulty was experienced at first in obtaining a satisfactory normal curve. The author was not aware that his vision was abnormal in any way, and expected to get a smooth curve as obtained by other observers of normal vision. After every set of readings, the curve proved to be irregular between .59μ and .66μ and it was thought for a time that this was due to the writer's inexperience in making such measurements. The readings were repeated again and again, the greatest care being taken to make correct observations, yet a smooth curve was never obtained through this region. After two weeks of strenuous work and several hundred measurements the writer was forced to realize that his color vision was not completely normal. The normal curve was finally plotted showing the abnormal elevation between .59μ and .66μ, the exact character of which was accurately determined by making observations on several additional points in this part of the spectrum.

Another difficulty experienced in obtaining a satisfactory normal was the gradual lowering of the entire curve as the constant re-reading of points continued from day to day. This gradual depression of the curve, which was most pronounced during the first three weeks and before a satisfactory normal was obtained, continued to drop very slowly for several weeks more. The phenomenon appears as one peculiar to the author himself, for three other observers, using the same apparatus and working under the same conditions for several months, did not experience it. One observer was noticeably color deficient in red, while the other two were of normal color vision and obtained almost identical persistency curves. Because of this gradual lowering of the normal the readings were repeated every few days, and if any appreciable change had taken place the fatigue or reflex curves, taken since the last normal observation, were discarded. It was found, however, after about one month's work that the normal remained almost constant. During continuous work from week to week the change in the normal, if any, was always a general lowering and never the reverse. However, on resuming the work after an interval of seven months, the normal had slightly raised, but came back to its original position after working for a week. In the second column of each table of data are given the readings of the normal curve against which the following reflex or fatigue curves are plotted.

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[4] Am. Jour. Sci. 44, 1892.

[5] Proc. Roy. Soc. 63, 1898; 70, 1902.

Table 1 *Normal Curves*

λ	Normals for Right Eye First	Normals for Right Eye Second	Normals for Right Eye Third	Normal Left Eye	Normal For F. A.	Normal For A. H.
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0329	0.0309	0.0301	0.0303	0.0335	0 0386
.720	.0277	.0256	.0249	.0253	.0287	.0316
.700	.0247	.0206	.0199	.0198	.0244	.0266
.680	.....	.0171	.0158	.0162	.....	.0229
.660	.0165	.0153	.0142	.0140	.0174	.0182
.640	.0158	.0148	.0136	.0133	.....	.0160
.620	.0144	.0138	.0125	.0126	.0152	.0147
.590	.0137	.0125	.0111	.0113	.0148	.0133
.570	.....	.....	.....	.....	.....	.0130
.550	.0142	.013	.0118	.0121	.0155	.0131
.530	.0152	.0141	.0126	.0129	.0165	.0138
.500	.0178	.0166	.0150	.0156	.0209	.0163
.480	.0210	.0200	.0187	.0191	.0255	.0191
.470	.....	.....	.....	.....	.0280	.....
.460	.....	....	.0233	.023	.....	.023
.450	.0298	.0276	.....	.....	.0336	.0257
.440	.....	.0307	.0300	.0313	.....	.0287
.420	.0416	.0396	.0404	.0423	.0431	.0372

Fig. 1 represents three stages in the lowering of the normal curve, the data of which are given in Table 1. The first normal plotted was that obtained after one week of steady work, the second after two weeks, and the third is the final curve which remained almost constant during the last five months. In Fig. 2 the author's final normal, marked W. A. A., is plotted with two other normals obtained by experienced observers, who used the same apparatus and worked under the same conditions. The curve marked F. A. is Allen's normal which is almost identically the same as obtained later by M. S. Hollenberg. The third

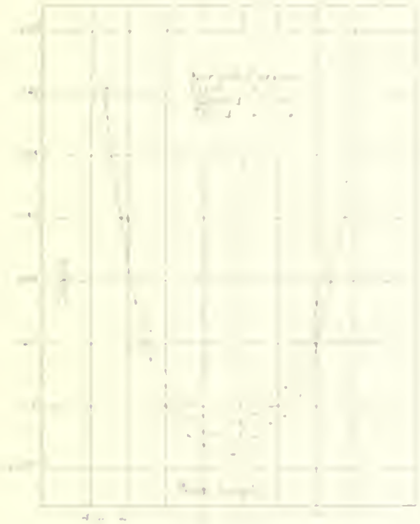

Fig. 1

Fig. 2

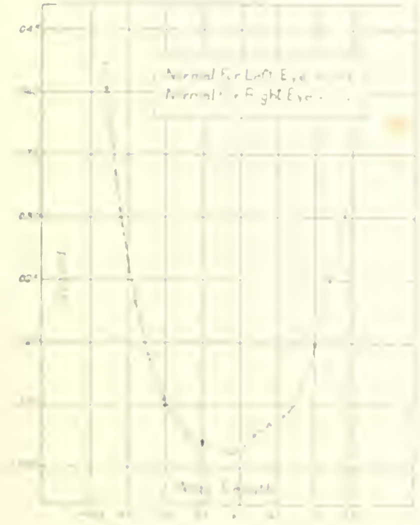

Fig. 3

Fig. 4

marked A. H., is that of A. Hollenberg, whose color vision is noticeably deficient in the red. A comparison of the author's persistency curve with the normal type, as obtained by Allen, indicates that the former's eye is much more sensitive to light of all wave lengths, the maximum difference being in the green and the minimum in the orange. As shown by Allen,[6] color deficiency is revealed by those portions of the persistency curve elevated above the normal type. This is well illustrated in A. Hollenberg's curve, which shows almost complete coincidence with the writer's throughout the violet and blue, but is greatly elevated, even above the normal type, in the yellow, orange and red.

At the close of the research a normal curve for the left eye was taken. This curve, plotted against the final normal for the right eye is shown in Fig. 3. It will be observed that it is of the same character as that for the right eye, the slight deviation being probably due to the fact, that the left eye was unaccustomed to taking readings. The data for all the normal curves discussed above are given in Table 1.

IV. Reflex Curves

All curves, plotted from results obtained by fatiguing the left eye and then making measurements on the spectrum with the right, are called reflex curves. The procedure was similar to that used to obtain a normal curve, except that the left eye was first fatigued for three minutes with the given spectral color. Care was taken in fatiguing the eye to fixate on the centre of the patch of color and to prevent the eye from wandering. The interval elapsing between the removal of the eye from the fatiguing color and the commencement of the chronographic record was from 15 to 30 seconds, while the time required to complete the record was about another 30 seconds. Since the left eye was fatigued for three minutes before every reading, and the time elapsing from one period of fatigue to the next seldom longer than a minute and a half, the eye was under almost continuous fatigue. The readings for an entire curve were usually taken at one session of two and a half to three hours. Any readings which were obviously inaccurate were repeated a few hours later, or, as was often the case, the next day. At least two or three hours, and usually one night, intervened between the taking of readings for two different fatiguing colors. In each figure two curves are plotted together to the same scale, one, the normal or reference curve, which throughout is shown as a dashed line, the second, the reflex curve, drawn as a continuous line. The coincidences and divergences of the reflex and normal curves show the effect of the fatiguing color in the left eye upon the physiological luminosity of the spectrum as perceived by the right.

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[6] Phys. Rev *11*, p. 257; 1900.

The deviation of the reflex curves from the normal is shown in another manner, at the bottom of each figure, by giving an arbitrary value of 100 to all points in the normal curve, and reducing the reflex curve in proportion. The data for all the reflex curves are given in Tables 2, 3 and 4. The fatiguing color used is marked at the bottom of the figures by an arrow.

Table 2. [illegible]

λ	Normal	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Sec.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
750μ	0.0335	0.0300	[illegible]	[illegible]	[illegible]	[illegible]
740	.0309	.0277	[illegible]	[illegible]	[illegible]	[illegible]
720	.0256	.0236	.0244	[illegible]	[illegible]	[illegible]
700	.0206	.0197	.0201	[illegible]	[illegible]	[illegible]
680	.0171	.0165	.0167	[illegible]	[illegible]	[illegible]
660	.0153	.0149	.0152	[illegible]	[illegible]	[illegible]
640	.0148	.0140	[illegible]	.0144	[illegible]	[illegible]
620	.0138	.0132	[illegible]	.0132	[illegible]	[illegible]
590	.0125	.0117	[illegible]	[illegible]	[illegible]	[illegible]
550	.0130	.0121	.0125	[illegible]	[illegible]	[illegible]
.530	.0141	.0133	[illegible]	[illegible]	[illegible]	[illegible]
500	.0166	.0160	[illegible]	.0165	[illegible]	[illegible]
480	.0200	.0193	.0205	[illegible]	[illegible]	[illegible]
450	.0276	.0266	[illegible]	[illegible]	[illegible]	[illegible]
440	.0307	.0287	[illegible]	.0312	[illegible]	[illegible]
430	.0350	.0327	[illegible]	[illegible]	[illegible]	[illegible]
420	.0396	.0370	.0365	[illegible]	[illegible]	[illegible]

The result of fatiguing the left eye with wave length .687μ is shown in Fig. 4. The entire curve is depressed below the normal, the depressions being greatest in the two ends and middle of the spectrum and least at the two points, about wave lengths .50μ and .66μ, which approximate the normal curve. It is evident that the effect of fatigue on the left eye has had a reflex effect upon the right, resulting in the enhancement of the physiological brightness of the entire spectrum. Fig. 5, which shows the result when the fatiguing color was .670μ, indicates an enhancement from the extreme red to .50μ and coincidence at .66μ and from .50μ to the violet end. When wave length .660μ was used to fatigue the eye, the reflex curve, Fig. 6, agrees closely with the normal in nearly all points, except for a slight depression in the orange, and a small elevation in the extreme violet, which may be partly due to the difficulty of making accurate measurements in this dim region of the spectrum. It is quite probable that some color close to .660μ, such as .663μ or .665μ, might be found to give a more complete coincidence. Wave length .660μ is one of the equilibrium colors discovered by Allen,[7] which shows no reflex enhancement in the other eye.

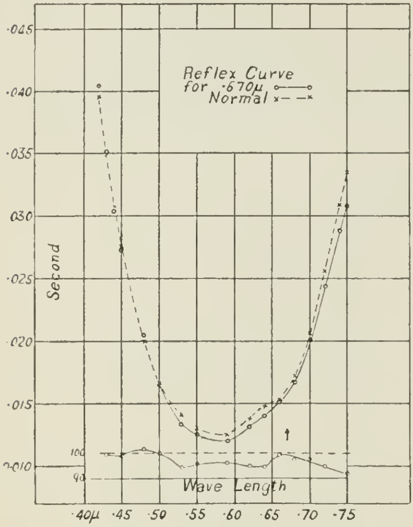

FIG. 5

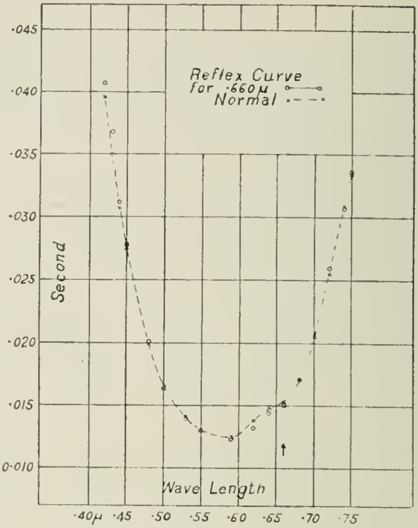

FIG. 6

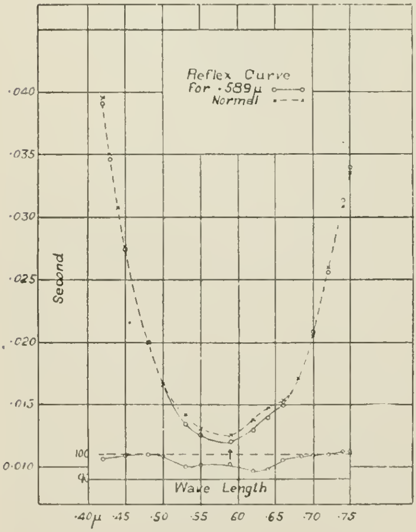

FIG. 7

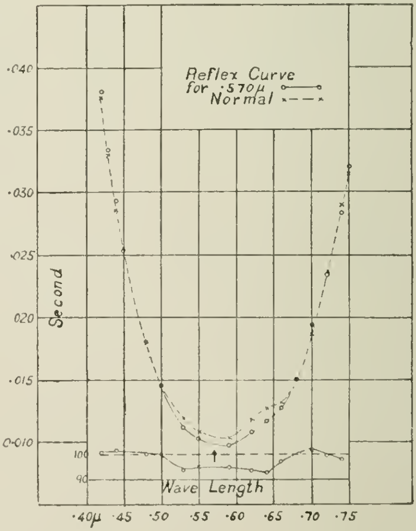

FIG. 8

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[7] Phil. Mag. *38*, p. 55; 1919. Also J. O. S. A. *7*, p. 583; 1923.

The reflex curve for a fatiguing color of .589μ, Fig. 7, shows a further reduction in the extent of reflex enhancement, as compared with Figs. 4 and 5. The enhanced effect is confined to the middle part of the spectrum between wave lengths .50μ and .66μ, while the remainder of the curve coincides with the normal. The transferred reflex enhancement for fatigue color .570μ, as shown in Fig. 8, is very similar to that for .589μ, except that the amount of enhancement in the orange is a little greater. Since wave length, .570μ, another of the equilibrium colors discovered by Allen, did not give the same result for the writer, another color near to it was tried, namely, .565μ. This proved to be an almost perfect equilibrium color, as shown in Fig. 9. The reflex curve for .535μ, as plotted in Fig. 10, shows, like some of the previous curves, an enhancement in the red and yellow-green, and coincidence with the normal from .50μ to the end of the violet. It differs from the other reflex curves by showing coincidence in the region corresponding to the abnormal part of the reference curve, which, however, includes .60μ.

Table 3. *Reflex Curves*

λ	Normal	.565μ	.535μ	.520μ	.480μ
	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0293	0.0291	0.0267	0.0276	0.0256
.720	.0254	.023	.0222	.0218	.0212
.700	.0190	.0188	.0181	.0199	.0173
.680	.0162	.0160	.0157	.0163	.0150
.660	.0142	.0143	.0142	.0141	.0138
.640	.0136	.0136	.0135	.0134	.0129
.620	.0127	.0126	.0128	.012	.0116
.590	.0113	.0113	.0109	.0114	.0108
.550	.0120	.0120	.0116	.0120	.0111
.530	.0127	.0129	.0125	.0129	.0130
.500	.0151	.0150	.0152	.0152	.0153
.480	.0178	.0175	.0177	.0180	.0180
.460	.0224	.0223	.0228	.0225	.0218
.440	.0299	.0297	.0306	.0302	.0290
.420	.0383	.0376	.0376	.0389	.0366

All fatigue colors chosen from the spectrum between wave lengths .520μ and .480μ resulted in giving good equilibrium curves very similar to Fig. 9. Curves for the following wave lengths were obtained, .520μ, .513μ, .505μ, .495μ, and .480μ, the data for which are given in Tables 3 and 4, but the curves themselves are not reproduced in this paper since they resemble closely Fig. 9. In this part of the spectrum Allen found three equilibrium colors, .520μ, .505μ and .480μ, while wave lengths .513μ and .495μ gave small reflex enhancements. Since most of the transferred reflex effects obtained by the writer are smaller than those shown by Allen's curves, it is quite probable that, if any reflex action is produced by either .513μ or .495μ in the writer's eye, it is too small to be detected.

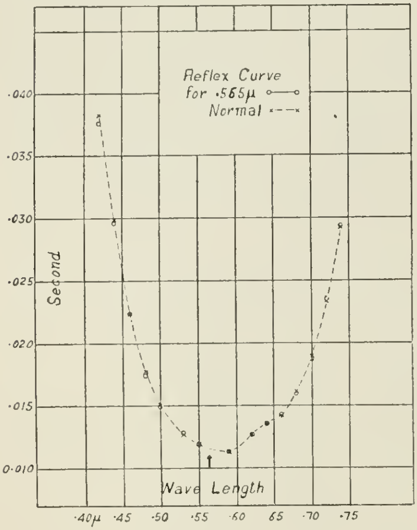

FIG. 9

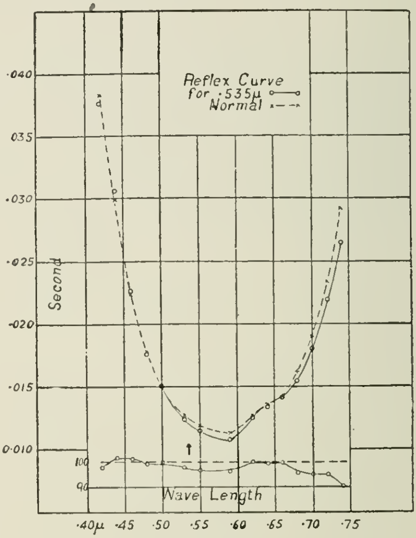

FIG. 10

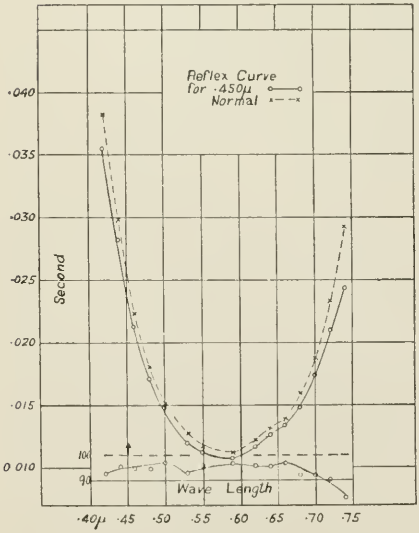

FIG. 11

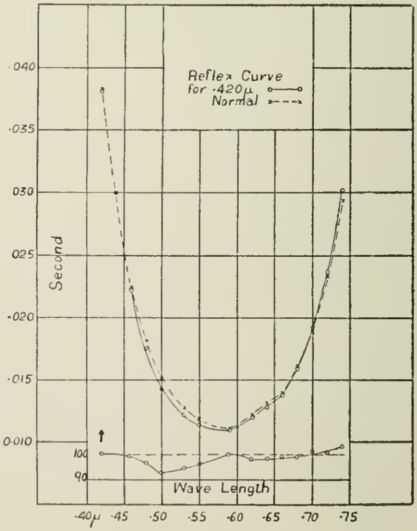

FIG. 12

The reflex curve for wave length .450μ as shown in Fig. 11 reveals a decided enhancement throughout the entire spectrum. The effect is most pronounced in the red, and least again about .50μ and .60μ. It may be observed that most of the reflex curves tend to coincide with the normal at these two points, which Allen has called "coincidence points." When wave length .420μ was used to fatigue the eye a small reflex enhancement was obtained, as shown in Fig. 12, but when .425μ was tried the reflex curve coincided throughout with the normal, thus giving the same equilibrium color as found by Allen.

TABLE 4.—*Reflex Curves*

λ	Normal	513μ	505μ	495μ	480μ	450μ	425μ	410μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0293	0.0287	0.0290	0.0293	0.0299	0.0245	0.0294	0.0263
720	0231	0231	0251	0233	0236	0210	0236	0217
700	0189	.0188	0189	0189	0187	0174	0189	0165
.680	.0161	0157	0160	0158	0158	0148	0160	0150
.660	0138	0137	0144	0133	0133	0134	0138	0140
.640	0131	0131	0133	0128	0132	0126	0132	0128
620	0122	0121	0122	0120	0121	0117	0121	0120
.590	0111	0111	0110	0112	0112	0108	0113	0111
.550	0118	0118	0117	0118	0118	0113	0120	0114
530	0128	0128	0125	0126	0126	0119	0127	0122
500	0152	0153	0150	0152	0148	0148	0153	0142
.480	.0181	0182	0178	0185	0179	0171	0183	0175
.460	0224	0225	0222	0229	0228	0213	0222	0225
440	0299	0295	0301	0301	0303	0283	0294	
.420	0383	0385	0386	0389	0383	0355	0389	0355

Although the luminosity of the violet fatiguing color was comparatively low, yet the largest reflex effects were obtained for the fatigue colors .450μ and .410μ. The results of the latter are shown in Fig. 13. Like .450μ, it produced a large enhancement throughout the entire spectrum except at the coincidence points .50μ and .60μ.

An examination of the reflex curves as a whole shows a very interesting fact, namely, that the largest reflex enhancements are not obtained by fatiguing with the brightest colors, but rather with the dim colors, such as .687μ, .450μ and .410μ. These wave lengths stimulate predominantly one sensation each; the first is confined almost entirely to the red sensation, while the latter two affect chiefly the violet. It would appear, therefore, that the large enhancements, obtained by fatiguing with the above colors, is due, either to their lower luminosity, or to the simplicity of their stimulations of the fundamental sensations.

A comparison of the various reflex curves shows that a reflex enhancement in the violet is obtained only when the fatiguing color is one of comparatively low luminosity, such as a red or violet. When a reflex does occur it is always manifested in the most luminous portion of the spectrum, and with the exception of the reflex curve for .589μ, also in the red. It was therefore of interest to determine the reflex effect of an intense white light.

The left eye was fatigued with a similar patch of white light, obtained by removing the prisms from a spectrometer and viewing the white light in the eyepiece. By this means, the area of the retina stimulated was the same as for the other fatigue colors. The results, as shown in Fig. 14, are similar to those obtained for bright colors throughout the middle of the spectrum. The curve from .48μ to the violet end coincides almost completely with the normal, while the remainder, with the exception of about .68μ, shows a distinct reflex enhancement. The data for this curve and the next are given in Table 8.

Before taking any readings for the reflex effect of darkness adaptation in one eye upon the perception of the luminosity of colors by the other, the left eye was blindfolded for about an hour, and kept in that state until all the observations, which were taken at the rate of one every five minutes, were completed. This curve, as plotted in Fig. 15, is quite different from any of the other reflex curves in that the entire curve, with the exception of the abnormal region .59μ to .66μ, is elevated above the normal. This clearly verifies the observations made by Allen, that dark adaptation in one eye lowers the physiological luminosities of colors perceived in the other, a fact, which shows the importance of investigating reflex phenomena in daylight, when the unused eye is under natural light adaptation.

The majority of the reduced curves, shown at the bottom of the figures, indicate a division into three parts, two of which correspond to the sensations of red and violet, while the third is in the middle portion of the spectrum, where green may be considered as the predominant sensation stimulated.

These curves fully verify the principle discovered by Allen, that the effect of fatigue, by a light stimulus in one eye, is transferred to the other by a reciprocal or reflex action of some kind, resulting in an enhancement of the physiological luminosity of the spectral colors perceived by the unfatigued eye. They differ from his in that the amount of enhancement is generally less, being sometimes very slight or even absent, especially in the blue and violet or that part which stimulates chiefly the violet sensation. The wave lengths of the equilibrium colors are approximately the same as found by Allen,

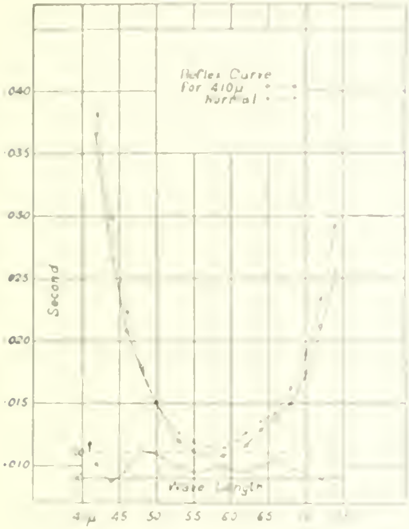

Fig. 13

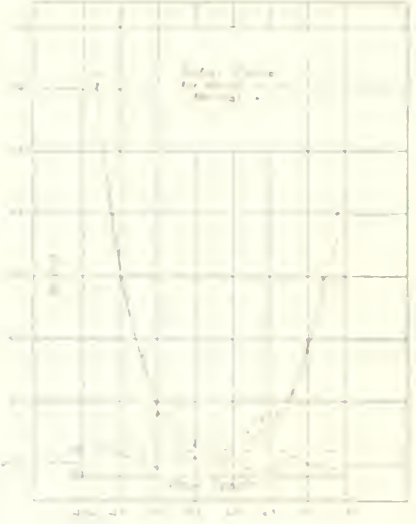

Fig. 14

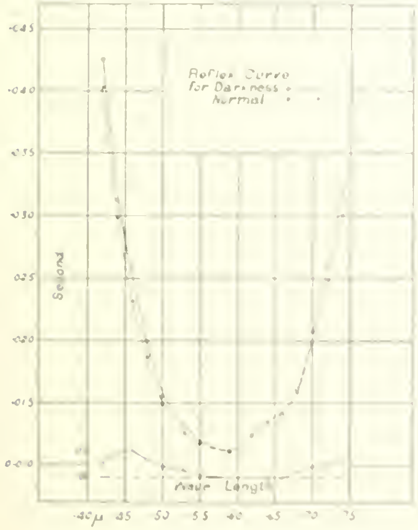

Fig. 15

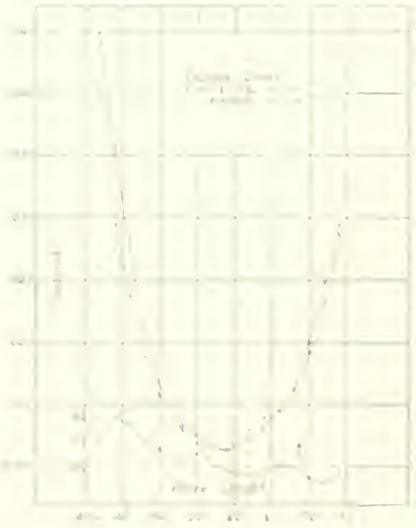

Fig. 16

except for the additional colors between .520μ and .480μ, which also gave very good equilibrium curves. The two coincidence points, .50μ and .66μ, also agree well with his.

V. Fatigue Curves

In this part of the investigations both the direct and reflex effects of fatigue in the same eye were studied. The same procedure was followed as for the reflex curves, except that the right eye was now fatigued and the measurements made on the same eye, while the left was maintained in daylight adaptation. The data for the fatigue curves are given in Tables 5, 6 and 7.

The first color used to fatigue the eye was wave length $.687\mu$, obtained from the arc light by means of a two prism Browning spectrometer. The results obtained were entirely unexpected, and it was thought that some error must have been made, either in recording the measurements, or in the use of the spectrometer providing the fatiguing color. Another spectrometer was taken and carefully recalibrated, and the curve repeated twice with the greatest care to get correct readings, first, using the arc spectrum to provide the fatiguing red, and second, an incandescent bulb. All three curves were identically of the same character, showing only small variations in the amount by which they deviated from the normal. One of the curves is shown in Fig. 16. Instead of getting an elevation in the red indicating fatigue, as was expected, a distinct depression was the result. The curve, after touching the normal at the coincidence point, about $.66\mu$, again shows another depression through the abnormal region. At $.59\mu$ it crosses the normal and gives an elevation throughout the remainder of the spectrum. It is to be noticed, that this is the first curve obtained showing smoothness throughout the region $.59\mu$ to $.66\mu$. It is evident, therefore, that the combined result of the direct and reflex effects of fatiguing with $.687\mu$, is to enhance the physiological luminosity of those parts of the observed spectrum corresponding to the depressions of the fatigue curve, and to decrease it for the parts showing an elevation. While measurements were being made on that part of the spectrum from $.62\mu$ to $.74\mu$, it was observed that the red appeared less saturated but brighter. The yellow appeared greenish, and the colors from $.55\mu$ to the violet end duller. The effect of fatigue began to pass off rapidly at the end of about one minute, as observed by the return of the natural appearance of the spectrum.

Fatiguing with $.670\mu$, Fig. 17, resulted in giving a curve very similar to the previous one, except that the deviations from the normal are more pronounced, especially the enhancement corresponding to the abnormal region of the reference curve. The effects of fatigue did not pass off nearly as rapidly as for .687μ. It has expected that the fatigue curve for .660μ would probably show almost complete coincidence with the normal, as was obtained for the reflex curve. Instead, however, as shown in Fig. 18, the curve is similar to the previous two, showing even a greater enhancement in red and also a greater fatigue in the yellow and green. The two coincidence points .50μ and .66μ are well marked. This curve was also repeated on another day after having carefully checked the normal, as was always done every few days. The results fully verified the first curve.

The three fatigue curves, now described for different wave lengths of red, show largest enhancements in regions about .72μ and .64μ, and greatest fatigue about .44μ. In an attempt to locate, if possible, an equilibrium color in the region of .660μ, wave length .665μ was tried as a fatiguing color, with the result that both curves show very good coincidence throughout the entire spectrum, as shown by the data in Table 5. A distinct difference in the effects of fatigue by .665μ and .660μ could be noticed on the red end of the spectrum, the former causing but little change in either saturation or apparent brightness, while the latter caused the red to appear noticeably less saturated but brighter.

TABLE 5. *Fatigue Curves*

λ	Normal	687μ	670μ	665μ	660μ
	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0295	0.0288	0.0287	0.0293	0.0280
.720	0248	0232	0229	0218	0218
.700	.0202	0193	0191	0194	0195
680	0163	0163	0163	0165	0168
660	0146	.0147	0142	0147	0144
640	0140	0133	.0130	0137	0132
620	.0130	0122	.0118	.0128	0124
.590	0115	0113	0112	0115	0120
550	0120	0126	.0119	0122	0127
530	0131	0134	0136	0132	0138
500	0158	0169	0168	0158	0162
480	0189	0209	0218	0197	0200
.460	0238	0282	0279	0236	0286
.440	0295	0356	0355	0295	.0344
420	0403	0450	0509	0410	0435

It was of interest to determine the effect of fatiguing the eye with a color selected from that part of the spectrum, which gives the abnormal elevation in the reference curve. Wave length, .630μ was selected and a fatigue curve obtained for it, the character of which is shown in Fig. 19. Like the other fatigue curves for red, a smooth curve was obtained without any trace of an irregular elevation between .59μ and .66μ.

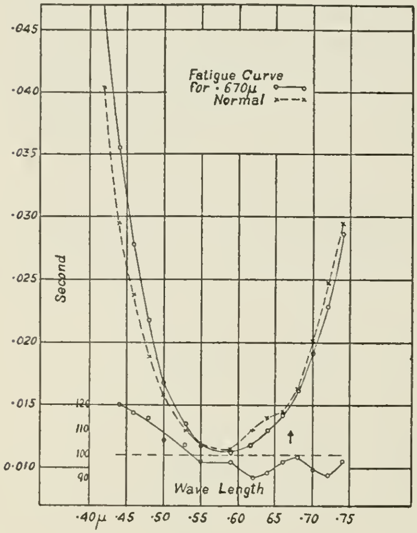

FIG. 17

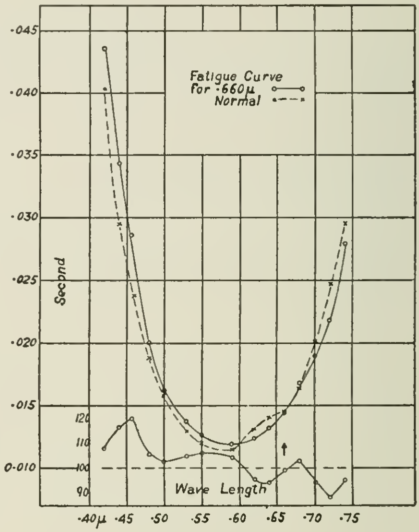

FIG. 18

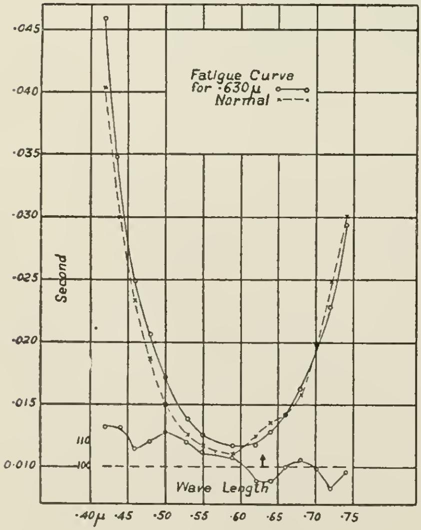

FIG. 19

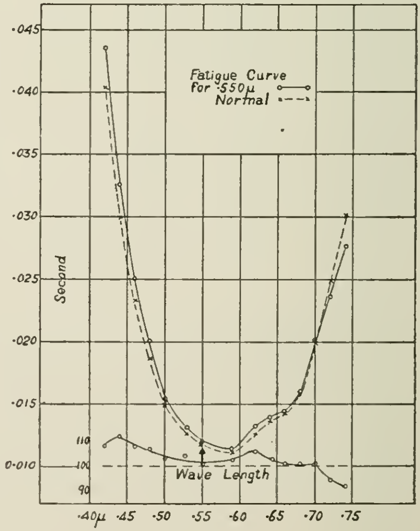

FIG. 20

As has been observed, the curves for wave lengths .687μ and .670μ both of which are on the same side of the equilibrium color, .665μ, are very similar; so, too, the curves for .660μ, and .630μ, on the other side of .665μ, show close resemblances. Wave length .650μ shows smaller enhancement in the red, but much larger fatigue in the green. The disproportionately large enhancement occurring about .72μ, as also referred to in the previous figures, is a noticeable feature. The observations on this point were repeated for nearly all the red fatigue curves, but in every case, the new readings confirmed the original.

When .589μ, the brightest color in the spectrum, was employed to fatigue the eye, another surprising result was obtained. As shown by the data in Table 6, the readings are almost identical with those for the normal curve, .72μ being the only point to show any appreciable variation, and this in the nature of a slight enhancement. For the writer's eye, therefore, wave length .589μ is an equilibrium color, when measurements are made on the fatigued eye. It may be recalled that even the reflex curve for .589μ, Fig. 7, coincided with the normal except in the middle part of the spectrum from about .53μ to .60μ. The fatigue equilibrium color, corresponding to .565μ of the reflex curves, was found when .570μ was employed. As shown by the data in Table 6, a very good agreement exists between the normal and most of the fatigue readings.

TABLE 6. *Fatigue Curves*

λ	Normal	650μ	570μ	550μ	[illegible]	[illegible]	[illegible]
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
740μ	0.0301	0.0295	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
720	.0249	.0228	.0242	[illegible]	[illegible]	[illegible]	[illegible]
700	.0199	[illegible]	.0191	.0092	[illegible]	.0095	[illegible]
680	.0158	.0163	.0155	[illegible]	.0170	[illegible]	[illegible]
660	.0142	.0142	.0141	.0141	.0145	.0144	[illegible]
640	.0136	[illegible]	.0133	.0140	.0141	.0134	[illegible]
620	.0125	[illegible]	.0124	.0132	[illegible]	[illegible]	.0124
590	.0114	.0117	.0112	.0114	[illegible]	.0115	[illegible]
550	.0118	.0125	.0117	[illegible]	.0120	[illegible]	[illegible]
530	.0126	.0139	[illegible]	.0131	[illegible]	[illegible]	.0125
500	.0150	.0172	.0157	.0154	[illegible]	[illegible]	[illegible]
480	.0187	.0206	[illegible]	.0201	.0201	[illegible]	[illegible]
460	.0233	.0249	[illegible]	.0251	[illegible]	[illegible]	[illegible]
440	.0300	[illegible]	.0207	[illegible]	[illegible]	[illegible]	[illegible]
420	.0404	.0469	.0414	.0435	[illegible]	[illegible]	[illegible]

The fatigue curves for wave lengths .550μ and .535μ are quite similar, as shown in Figs. 20 and 21. Both show an enhancement in the extreme red, fatigue in the yellow, orange and orange-red, very little change in the green, but considerable fatigue in the blue. In the violet there is a difference, one showing distinct fatigue, the other coincidence except for a slight enhancement in the last point.

Fig. 22 shows the curve for fatigue color .520μ, which, although not quite an equilibrium color, yet suggests that a slightly shorter or longer wave length would result in such. When making observations for the reflex curves, all colors between .520μ and .480μ showed no change in the persistency curve, but when these same colors were employed to obtain fatigue curves none were found to give equilibrium effects. Figs. 23, 24 and 25, show the curves for the fatigue colors, .513μ, .505μ and .480μ respectively. All three curves are somewhat similar, showing fatigue to a greater or less degree in all parts, except in the extreme red and violet. Wave length .513μ, however, indicates also a fatigue of the extreme violet. According to the intersections of the equal area sensation curves of König and Dieterici,[8] this portion of the spectrum is quite complex and it is, therefore, not surprising that almost all parts of the spectrum should show fatigue. On the other hand, the largest reflex effects in the unfatigued eye were obtained for the comparatively pure colors, red and violet, which arouse predominantly one sensation each and but slightly the other two. Since white light, and most colors stimulating the three sensations to a considerable degree, produce comparatively small reflex results, it is not surprising that the above mentioned complex region of the spectrum should give equilibrium reflex curves.

The fatigue curves for wave lengths .450μ and .425μ, Figs. 26 and 27, show fatigue in all parts of the spectrum, the former, except in the extreme red, to a much more marked degree. It may be observed from these two curves, and also from .480μ, that greatest fatigue is shown in that part of the spectrum corresponding to the fatiguing color. When the dim violet, .410μ, was employed, the fatigue was only evident in the less bright parts of the spectrum, as shown in Fig. 28. It is possible, that the considerably brighter region of the spectrum, from .50μ to .66μ, rapidly overcame the state of fatigue due to the dim violet. It is also possible, that the eye was under partial darkness adaptation, due to the comparative darkness of the spectrometer tube, in the centre of which, the dim violet was fixated for three minutes out of every four. This latter possibility seems the more probable in view of the effect of darkness adaptation on the same eye with which the measurements are made. This effect is shown in the next curve.

[8] Parsons: "Colour Vision" p. 222.

Before taking any readings for the fatigue curve for darkness, as it may be called since the results are similar to fatigue, the right eye was bilndfolded for about one hour. Readings were made on the spectrum,

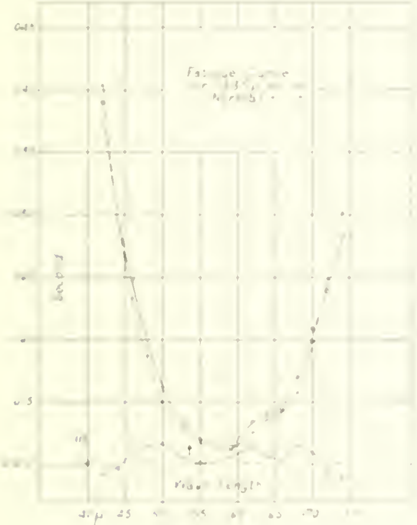

FIG. 21

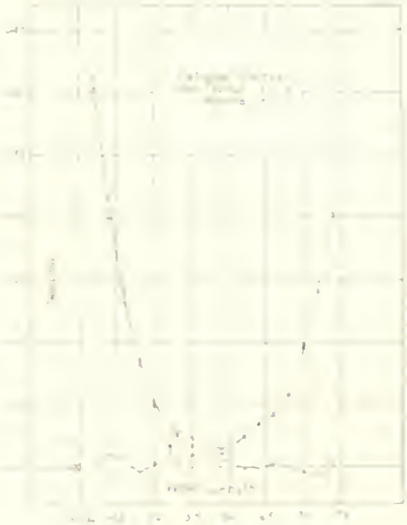

FIG. 22

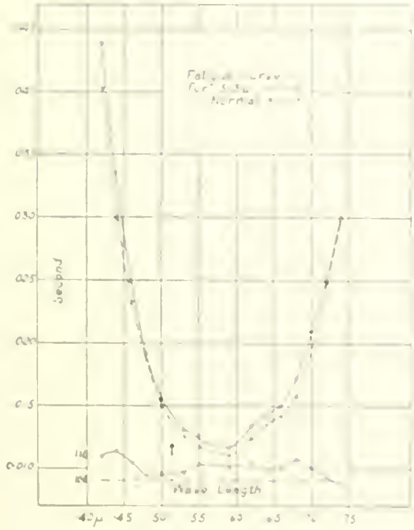

FIG. 23

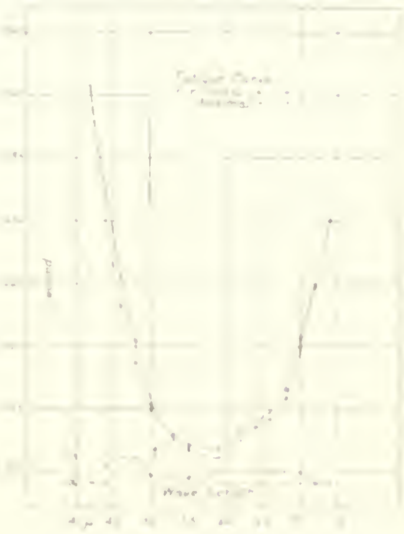

FIG. 24

still in the daylight room, by uncovering the eye for the brief period of about thirty seconds which was required to make the chronographic record. While uncovering the eye and placing it in the shield attached to the spectrometer eye piece, care was taken to prevent any daylight from entering the eye. Between readings the eye was kept blindfolded for five minutes. Although the appearance of the spectrum to the dark adapted eye was such as to suggest an increase in the brightness, yet the true effect must be judged by the actual measurements obtained. These measurements, as plotted in Fig. 29, clearly show that the effect of darkness adaptation is to lower the physiological luminosity of the spectrum, a fact, which was pointed out by Allen[9] over twenty years ago. The effect, as obtained by the writer, is not marked in the most luminous part of the spectrum. This may be caused by the rapid disappearance of the effects of darkness adaptation in the presence of the comparatively bright spectral colors, upon which the measurements were being made; for it has already been pointed out, that the author's eye is much more sensitive than normal to a light stimulus.

TABLE 7. *Fatigue Curves*

λ	Normal	.513μ	.505μ	.480μ	.450μ	.425μ	.410μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0301	0.0299	0.0300	0.0292	0.0305	0.0313	0.0320
.720	.0249	.0250	.0248	.0257	.0258	.0259	.0264
.700	.0199	.0210	.0208	.0210	.0222	.0217	.0220
.680	.0158	.0172	.0166	.0173	.0177	.0174	.0168
.660	.0142	.0150	.0148	.0151	.0150	.0150	.0144
.640	.0136	.0142	.0136	.0140	.0145	.0140	.0138
.620	.0125	.0134	.0130	.0136	.0134	.0134	.0129
.590	.0111	.0117	.0117	.0119	.0121	.0115	.0110
.550	.0118	.0126	.0121	.0126	.0128	.0123	.0117
.530	.0126	.0130	.0129	.0137	.0133	.0133	.0124
.500	.0150	.0155	.0154	.0176	.0171	.0162	.0152
.480	.0187	.0192	.0205	.0213	.0220	.0208	.0195
.460	.0233	.0250	.0256	.0248	.0280	.0262	.0252
.440	.0300	.0335	.0322	.0314	.0349	.0336	.0322
.420	.0404	.0440	.0408	.0400	.0427	.0457	.0417

To obtain a fatigue curve for white light, the eye was fatigued by a moderately bright light, transmitted through a spectrometer with the prisms removed, as was the case for the reflex curve. A very brilliant light made it almost impossible to get consistent readings because of the vivid after images produced. The readings from which Fig. 30 was plotted showed, however, good agreement. The character of this curve is interesting in the relation which it bears to all the other fatigue curves. This curve is really the combined effect of the main types of fatigue-curves, for it reveals a large fatigue in the yellow, green, blue and violet colors, as is also shown to a greater or less extent by nearly all the fatigue curves, but shows little or no fatigue in the red

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[9] Phys. Rev. *11*, p. 265; 1900.

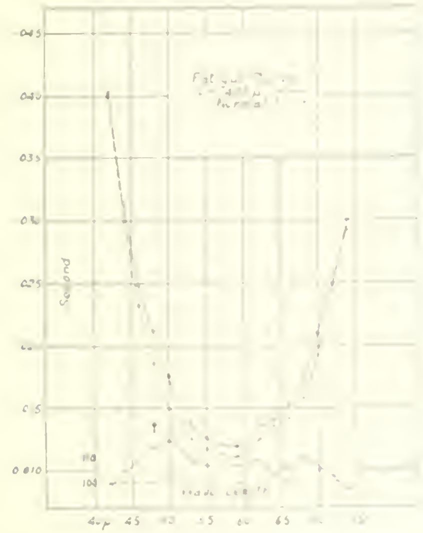

FIG. 25

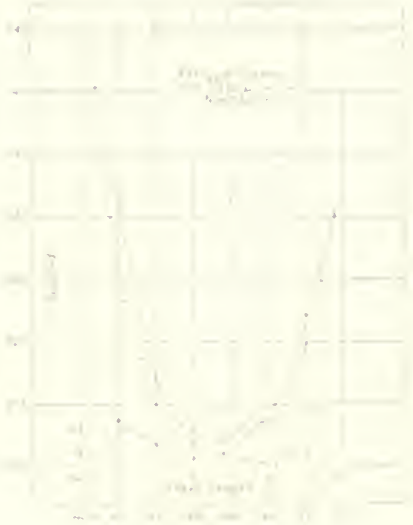

FIG. 26

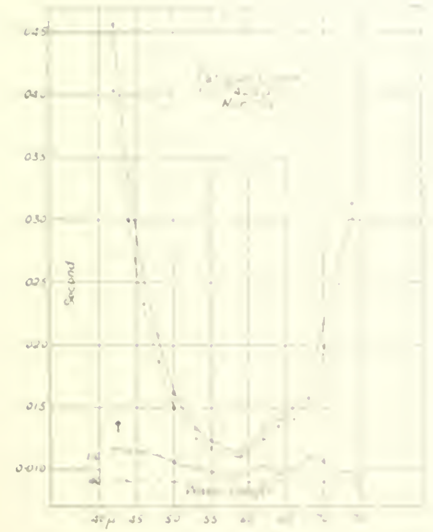

FIG. 27

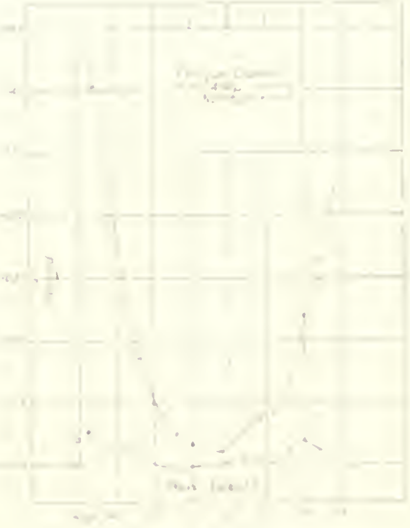

FIG. 28

end of the spectrum, a result which is about the average effect for all the fatigue colors. The data for the two curves for white light and darkness are given in Table 8.

A general survey of all the fatigue curves, except those for equilibrium colors, reveals three fairly distinct types, which change more or less gradually from one type to the other. When the fatiguing color is any hue of red, there is always an enhancement in the extreme red and orange-red, the amount of which is less for the fatigue color, .630μ than for those of longer wave length. The depression in the brightness of

TABLE 8. *Light and Darkness Curves*

λ	Normal	Reflex Darkness	Fatigue Darkness	Reflex White	Fatigue White
.740μ	0.0301	0.0320	0.0323	0.0281	0.0301
.720	.0249	.0260	.0259	.0234	.0257
.700	.0199	.0208	.0220	.0190	.0197
.680	.0158	.0162	.0165	.0155	.0162
.660	.0142	.0139	.0148	.0132	.0148
.640	.0136	.0133	.0140	.0125	.0137
.620	.0125	.0125	.0127	.0116	.0128
.590	.0111	.0110	.0110	.0106	.0120
.550	.0118	.0118	.0115	.0115	.0128
.530	.0126	.0131	.0128	.0121	.0138
.500	.0150	.0156	.0157	.0139	.0165
.480	.0187	.0201	.0198	.0183	.0205
.460	.0233	.0259	.0260	.0228	.0260
.440	.0300	.0312	.0340	.0298	.0339
.420	.0404	.0426	.0462	.0413	.0459

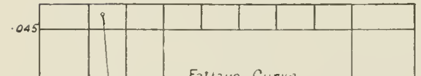

FIG. 29

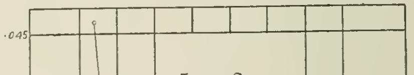

FIG. 30

the green region of the spectrum increases in amount with a decrease in the wave length of the red fatiguing color, while the violet end shows always a distinct lowering of the physiological luminosity. The equilibrium curves for yellow fatiguing colors separate the red type from the green, or second type. Fatiguing with green gives an enhancement in the red, the amount of which decreases as the fatigue color moves towards the blue, the blue showing little or no effect on the longer red waves; on the orange-red the effect is a lowering of the brightness, the amount of which increases with a decrease in the wave length of the fatigue color. Green fatigue curves also show a depression in the brightness of the green, blue and violet colors, the amount of which increases as the fatigue color becomes more blue.

The second type changes gradually through the fatigue curves for blue to the third type, which is for violet fatiguing colors. The transition curves in the blue show but little fatigue or enhancement for the extreme red or violet, and an increasing fatigue in the brighter colors. The violet curves give a depression in luminosity throughout the entire spectrum, the amount of which decreases as the fatiguing color approaches the extreme end of the spectrum, until for 410μ the brighter part of the spectrum shows no change.

The reduced curves at the bottom of the figures show a tendency to divide, in most cases, into three regions, which are not regular enough in all the curves to say that they indicate always the three fundamental sensations, red, green and violet. The existence of these three fundamental sensations is indicated more particularly by the natural division of the curves into the three main types as already described.

VI. Theoretical Considerations

The experimental results, which have now been considered, fully verify Allen's discovery of the dual action of light in arousing visual sensations. Although the character of many of the curves, given in this paper, differ considerably from his, yet they clearly show that in addition to the direct effect of light, which tends to produce fatigue, there is also a reflex effect, resulting in an enhancement of the fundamental sensations. Several of the reflex curves are very similar to Allen's, showing that, when a light stimulus falls upon one eye, the sensory reflex is transferred to the other causing an enhancement of all three sensations. Certain colors, which are termed equilibrium colors, apparently produce no effect in the physiological brightness of the colors perceived by the unfatigued eye, while fatigue by still different wave lengths enhances only the red and green sensations in the opposite eye and not the violet. The violet sensation in the writer's eye seems the least sensitive to stimulation by a sensory reflex, transferred from one eye to the other.

In the same eye, Allen found that the direct effect of a color stimulus was to cause a diminution in the physiological brightness of the colors, corresponding to the primary color sensations represented in the fatiguing color, and that the reflex effect was to enhance the brightness of those colors which stimulate chiefly the complementary sensations.

The majority of the author's fatigue curves, however, are quite different from those obtained by Allen. When red of any wave length, except .665μ, was employed as the fatiguing color, the result was not a diminution in the brightness of the red, observed in the other spectrometer, and a corresponding enhancement of those colors representing predominantly the green and violet sensations. Instead, the red sensation was actually enhanced, the violet fatigued, and the green little affected, except by the shorter red waves which fatigued it. Stimulation with green shows fatigue in the green and violet and enhancement in the red, but violet, however, fatigues more or less all three sensations.

Although these results are not of the normal type, yet it is evident that the conclusions drawn from Allen's researches do not give a complete statement of the direct and reflex stimulation of the fundamental color sensations when light falls upon the retina. A more comprehensive statement, which is based on the results shown by the curves in this paper, may be expressed as follows:

Light of every hue falling upon the retina affects all three sensations both directly and reflexly. For example, a green light stimulates by direct action all three sensations, but predominantly the green, and by reflex action also the three sensations, but predominantly the red and violet. The direct effect always tends to produce fatigue, and the reflex, enhancement. In normal vision under ordinary conditions, if we again take green as the fatiguing color, the direct effect on the green sensation overbalances the reflex action on the same sensation, resulting in a fatigue of the green sensation; and the reflex effect on the complementary sensations, red and violet, overbalances the direct effect on the same sensations, thus producing enhancement of the complementary sensations. While the eye is still being stimulated by the green light, the direct effect usually predominates over the reflex, the net result being a sensation of green with an underlying whiteness which increases with fatigue. However, under certain conditions, and especially in cases of abnormal vision, the above is not always the net result of direct and reflex stimulation of the sensations. The discussion of this point, however, will be postponed until after the author's type of abnormal vision has been considered.

Helmholtz suggested that every ray in the spectrum affected each of the three sensations, red, green and blue. Abney in referring to Helmholtz's suggestion states:[10] "If Helmholtz's diagram (p. 41) were correct, one colour would never stimulate one sensation by itself. As it is, however, the red stimulates only the red sensation in one part of the spectrum, whilst the violet stimulates both the red and the blue and not the green sensations. A green color stimulates not only the green sensation, but it stimulates the red and blue as well as is shown in Helmholtz's diagram. The trichromatic theory requires this to be the case." The experimental results given in this paper show that Helmholtz was right in his assumptions, although unaware that the three fundamental color sensations are stimulated reflexly as well as directly by every hue. Abney failed to detect the dual nature of the action of light upon the retina, partly, no doubt, because of the negative effect of darkness adaptation, and partly because many of his observations were based on the assumption that light falling upon one eye has no effect upon the other, a conclusion which these researches show to be incorrect.

ANOMALOUS TRICHROMATISM

The author has no difficulty whatever in passing ordinary wool and card tests for color deficiency, nor has he at any time experienced any phenomena apart from these experiments to indicate that his vision is in any way abnormal. Slight pleochroism in certain minerals under the polarising microscope can be observed, even when the effect is too weak to be detected by as many as one quarter of a class. There is also no shortening of the spectrum at either end as compared with those whose color vision is undoubtedly normal. However, a comparison of the author's normal persistency curves, and especially his fatigue curves, with those obtained by Allen, indicates that an abnormality of some sort certainly exists. Allen's curves have been fully confirmed by M. S. Hollenberg,[11] who not only obtained the same normal curve but also the same type of reflex and fatigue curves. Their results appear therefore, as those of observers whose color vision is in every way normal.

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[10] "Researches in Color Vision," p. 230.

[11] J. O. S. A. & R. S. I., 8, p. 713, 1924.

A comparison of the author's normal curve with that of Allen, Fig. 2, shows that the greatest deviation is in the green and yellow, or that part which corresponds predominantly to the green sensation, and the least departure from the normal type in the orange and orange-red, from $.59\mu$ to $.66\mu$. An examination of the sensation curves of König and Dieterici,[12] shows that the green sensation falls to zero in this region. Although, in light of the principle of reflex stimulation of sensations, all three sensation curves should extend to the ends of the visible spectrum, yet the above mentioned curves are no doubt correct in indicating that, at least, the direct stimulation of green beyond $.66\mu$ is very small. The elevation in the author's normal curve between $.59\mu$ and $.66\mu$ would appear, therefore, to be due to a deviation of the green sensation curve, rather than the red, from that of the normal type. It seems probable that, if the writer's sensation curves were determined and plotted as equal area curves after the manner of those of König and Dieterici, the green sensation curve would be found to show a depression, as compared with the normal type, for the region between $.59\mu$ and $.66\mu$, and a corresponding elevation throughout the yellow and green parts of the spectrum.

It is well known that there are individuals, who show no color deficiency whatever, but who, in matching a spectral color, by two mixed colors, differ in their equation from that of the normal. For example, when making the equation, $.670\mu+.535\mu=.589\mu$, some require more red and others more green than the normal. Those requiring more red are commonly called red anomalies, and those requiring more green, green anomalies. Edridge-Green states,[13] "There are also those who will make normal equations when the red employed is λ670, but will make an anomalous equation with a red of larger wave length, as for instance λ690, putting in twice as much red in the mixture compared with the normal equation in similar circumstances." It is quite conceivable that an individual, who is not color deficient, may not only agree with the normal in the equation, $.670\mu+.535\mu=.589\mu$, but also with a few other equations, and yet differ from the normal when still different wave lengths are employed. Such individuals must be classed as anomalous trichromats.

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[12] Parsons: "Colour Vision," p. 222

[13] 'Physiology of Vision," p. 223.

As the results of the experiments given in this paper were studied more closely it became more convincing that their abnormal character must be due to anomalous trichromatism. It therefore became desirable to test the author's color vision by means of color equations.

The apparatus used was Allen's trichromatic spectrometer[14] in which two colors can be isolated and mixed in the upper part of the shutter eyepiece, and a single color in the lower part. Each of the three colors were obtained from the separate spectra of three acetylene flames of constant luminosity. The intensity of a color was altered by opening or closing the collimator slit.

The first equation attempted was $.670\mu + .535\mu = .589\mu$, but in this the author agreed with the normal equation as obtained by Allen and others. It will be noticed by reference to the normal curve, Fig. 2, that these three wave lengths are outside of the writer's particularly abnormal region, $.59\mu$ to $.66\mu$. The red was then changed to a longer wave length $.690\mu$, but again the difference was not sufficient to say that an actual disagreement existed. The same was true when a longer wave length of $.720\mu$ was used instead of $.690\mu$. The next step was to select a wave length from the abnormal region, $.59\mu$ to $.66\mu$, as one of the three colors. The first equation made was $.670\mu + .535\mu = .630\mu$. In this case, when the match was perfect for the normal eye, it appeared distinctly too yellow to the writer, and the amount of green had to be decreased to give a good match. When the red was changed to $.690\mu$ and $.720\mu$ the same results were obtained.

Wave length $.630\mu$ affects chiefly the red and green sensations, and since a less amount of green, or a greater amount of red, is required than normal to match $.630\mu$, it is evident, that either the green sensation is comparatively less stimulated, or the red more stimulated than normal by colors between $.59\mu$ and $.66\mu$. A comparison of the writer's normal persistency curve with that of a normal trichromat, as has already been pointed out, would indicate that the abnormalty is due to an over sensitiveness of the green sensation to wave lengths of the yellow and green regions of the spectrum, and to an under sensitiveness of the same sensation to wave lengths between $.59\mu$ and $.66\mu$. In this respect, therefore, the author is an anomalous trichromat, but according to the general distinction between green and red anomalies he would be classed as a red anomaly, since he requires more red in the equations than the normal.

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[14] J. O. S. A. & R. S. I., 5, p. 339, 1921

Anomalous trichromatism, and in fact color vision in any phase, cannot be studied fully unless both the direct and reflex action of a light stimulus on the retina be taken into consideration. Heretofore, only the direct effect of light was considered, and that not generally to the extent that every ray affects, to a greater or less extent, all three sensations. An individual may be not only anomalous in respect of the direct effect of light, but also anomalous in the development of his reflex sensations. The latter phase is probably most easily detected after prolonged stimulation, since the reflex sensation, which may be set up in a very small fraction of a second, increases with continued stimulation.

While fatiguing the eye with a brilliant green light it was observed that, at the end of about 25 seconds, the light began to lose its green color and to assume a purple tinge, which increased in saturation for another 25 seconds, at the end of which the color appeared more purple than green; the purple then gradually decreased until, at the end of about 90 seconds, it again appeared a dull green of much reduced intensity and saturation. A similar effect was observed when fatiguing with a strong white light. The white light became distinctly pink, which gradually increased for a short time and then slowly disappeared as the fatigue reached a maximum. However, when using a brilliant red light no tinge of green could be observed although at first it was expected. These observations may be readily explained as follows:—

An examination of the fatigue curves shows that the author's violet sensation is easily fatigued by nearly all hues to a greater or less extent. From the reflex curves, it may also be seen, that violet perceived by the other eye is not markedly enhanced by a transferred reflex stimulation, except when the fatiguing color is near either end of the spectrum. It therefore appears, that with prolonged stimulation, the net result of the direct and reflex action of the different hues upon the violet sensation is nearly always in favor of fatigue. Fatigue curves show, that the green sensation is also fatigued by most hues, but the fatigue, except by a few colors, is not marked. Reflex curves, on the other hand, show, except for equilibrium colors, fairly distinct enhancements. The red sensation, however, is very difficult to fatigue and shows fatigue only in the extreme red and only when the fatiguing color has a wave length of $.480\mu$ or less. According to the sensation curves of König and Dieterici the red sensation curve terminates at about $.480\mu$. It has already been pointed out that the experimental evidence given in this paper, would indicate that the red sensation curve really extends to the violet end of the spectrum as Exner's curves show.[15] However, the curves of Konig and Dieterici may be taken as showing that the direct stimulation of the red sensation by wave lengths longer than .480μ is at least very small. If the fatiguing color is any hue of red or green, except equilibrium colors, the fatigue curves show that the effect of prolonged stimulation is an enhancement of the red sensation, due to the reflex action overbalancing the direct. The reflex curves also show that the red sensation is far more susceptible to reflex stimulation than the other sensations. It must be remembered, of course, that the experimental results were obtained by removing the eye, after strong stimulation for three minutes, to a less intense spectrum upon which the measurements were made. Therefore, when a bright white light is fixated by the author's eye for about 30 seconds it assumes a pink tinge due to the strong enhancement of the red sensation by reflex action. With longer fixation the direct effect overtakes the reflex and fatigue predominates, with the result that the pink tinge disappears leaving a white of a much reduced intensity. Similarly, when a brilliant green color is fixated, the reflex enhancement of the red sensation, which is the sensation predominantly stimulated by the reflex action of green outgrows the green sensation, which is being fatigued by direct stimulation, thus resulting in giving the color a purplish tinge. Longer fixation again results in favor of the direct action on the green and the color appears a green of a much reduced luminosity and saturation. However, when fixating upon a brilliant red color, the author's red sensation is so difficult to fatigue, and so sensitive to enhancement by reflex action, that the reflex green never outgrows the red, and therefore no green tinge was ever observed when fatiguing with red.

Although anomalous trichromatism may, in part, be explained as due to a shift of one of the sensation curves, yet the experimental evidence given in this paper shows that a more comprehensive explanation is possible. Since direct stimulation of the retina is always accompanied by a sensory reflex, then any abnormal development of the reflex stimulation must produce at least anomalous results in color vision. In general, therefore, anomalous trichromatism is due to an abnormal ratio of the direct stimulation of the sensations to their reflex enhancement. Since this ratio depends to some extent upon the intensity and duration of a stimulus, it is quite conceivable, as Edridge-Green has observed, that[16] "There are also persons who will make normal equations in one set of circumstances and anomalous equations in another." He has also observed, as already referred to in a previous quotation, that some individuals will agree with the normal equation when a red of wave length .670μ is used but will make an anomalous equation with a red of .690μ. Now, .670μ is very close to an equilibrium color which the author found to be at .665μ, while .690μ is a color which gives large reflexes. It is quite possible, therefore, that these anomalous trichromats, examined by Edridge-Green, had an equilibrium color close to .670μ, the stimulation of which would result in a balance being set up between the direct and reflex effects of the color, while the effect of employing a red of .690μ would be to produce abnormal reflex enhancements and consequently an anomalous equation.

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[15] Parsons: Colour Vision, p. 223.

[16] "Physiology of Vision," p. 223.

The following observations, made by various experimenters, clearly show when viewed in the light of this paper, that the reflex sensation may, under certain conditions and with certain individuals, actually predominate over the direct effect of a light stimulus.

"If the primary stimulus (white) is more intense or acts for a longer time coloration may commence before obscuring the eye (Fechner)."[17]

"A vivid blue-green after image may be seen not only in the absence of all green light but whilst the eye is still being stimulated with a red light."[18]

"The case of a strongly colored red surface whose image extends over the greater part of the retina is especially striking. The colour fades very slowly but steadily, giving rise to a peculiar sensation of loss of power of the eye until the field becomes quite grey and colourless. At this stage the state is one of kinetic equilibrium, and a subjective fluctuation, like those which are always taking place in self light, may suddenly result in a rise of the threshold values of the weak green and blue sensations. If that occurs the colour of the field will suddenly flash into perception as a strong green. The effect is unusually striking, but is not easy to attain."[19]

This last quotation is really a careful description of what may be called the growth of the reflex sensation until the effect of direct action, which affects predominantly the red sensation, is equalled by the reflex action, which enhances chiefly the complementary green, thus resulting in a grey. An equilibrium between the two effects then exists until the reflex enhancement of green suddenly predominates over the direct excitation of red

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[17] Parsons: "Colour Vision," p. 110.

[18] Edridge-Green: "Physiology of Vision," p. 145.

[19] Peddie: "Colour Vision," p. 175.

THE APPLICATION OF THE PRINCIPLE OF REFLEX VISUAL SENSATIONS TO THE YOUNG-HELMHOLTZ AND HERING THEORIES

The Young-Helmholtz trichromatic theory of color vision with the various modifications and extensions, made by von Kries, Abney and others, furnishes a simple and satisfactory explanation of a great mass of phenomena associated with the perception of light and color. The theory originated out of a study of color mixtures, which are explained by it in a very satisfactory manner. Dichromatic vision is explained as due to the absence of one of the sensations, and monochromatic vision as the identity of all three. Anomalous trichromatism, according to this theory, is due to a partial reduction in one or more of the sensations, or in some types, to a shift in one of the sensation curves.

The theory, apart from the principle of reflex sensations offers no adequate explanation of the phenomena of after images, for both positive and negative after images may be experienced in the absence of stimulation by white light. If dichromatic vision is due to the absence of one component sensation, it is difficult to understand why a certain portion of the spectrum should be seen as grey and not colored, if the remaining two sensations are stimulated, nor almost completely dark, if none of the sensations be affected. Again, it does not appear consistent to suppose, that dichromatic vision is due to the absence of one color sensation, while monochromatic vision is the identity of the three. The theory is also deficient in offering an explanation for the various types of color blindness with normal luminosity curves. The facts of spatial induction or simultaneous contrast were regarded by Helmholtz as "illusions of judgment," an explanation which abandoned physiology completely.

These researches are not intended to confirm the Young-Helmholtz theory, although they do indicate three fundamental sensations corresponding to red, green and violet. The evidence rather corrects and extends the theory by recognizing the reflex action of light upon the visual mechanism in addition to its direct effect.

This addition of the principle of reflex visual sensations, as discovered by Allen and as extended both by him and in this paper, offers on the basis of the trichromatic theory, simple and satisfactory explanations for successive and simultaneous contrast, the whiteness underlying all colors, the saturation of color in after images, complementary colors, anomalous trichromatism, etc. von Kries' duplicity theory, which offers an explanation of scotopic or twilight vision, may yet prove an unnecessary addition, for, as all colors tend to become white at high intensities, due to the reflex enhancement being equal to the direct, so too, the absence of color in all lights at low intensities may be due to another equality between the direct and reflex action of light in stimulating the sensations. It is quite possible that color blindness, either partial or complete, may also be caused by certain balances set up between the direct action of light and the complementary reflex, resulting in grey. The correctness of the above predictions can only be determined, in the first case, by an experimental study of reflexes at low intensities, and in the second by investigating them in the color blind.

The value of any theory is twofold, first, in offering satisfactory explanations of many related phenomena, and second, in stimulating fruitful research. In this respect the trichromatic theory of Young-Helmholtz has become more and more firmly established, until now, in the light of the recent researches in reflex visual sensations, little room seems left for many of the opposing theories. However, it seems quite improbable that a rival theory, which also explains many phenomena of color vision, and which too has stimulated much valuable research, should not contain a considerable degree of truth. Such a theory is that proposed by Hering.

The Hering theory assumes six psychophysical processes, corresponding to the six primary sensations, which may be arranged in pairs, red-green, yellow-blue, white-black. Three photochemical substances are supposed to exist in the retina, one corresponding to each of the three pairs of sensations. The first named sensation in each pair is supposed to arise from the dissimilation of the photochemical substance and the second sensation from its assimilation. All rays of the visible spectrum have a dissimilating action on the white black substance but different wave lengths in different degrees. When mixed light produces equal dissimilation and assimilation in the red-green or the yellow-blue substances, colorless light is the result. The action is not complementary but rather antagonistic, for yellow and blue do not produce white light by their combination, but by destroying each other's effects, and leaving visible the white, which is already there through the dissimilation of the white-black substance by the mixed light. Each visual response is therefore a mixture of the three sensations excited by dissimilation together with the three arising from assimilation, the resulting color being due to the one of the six that produces relatively the greatest effect.

The principles deduced from the experimental evidence given in this paper show that two opposite effects are produced whenever light of any hue stimulates the retina. The direct and reflex action of light, although apparently antagonistic, produce their full effects without in any way destroying or inhibiting each other. The net result is not the excess of one action over the other, but rather the combined effect of the two. Because of the underlying whiteness of all spectrum colors, Hering assumes the existence of a white-black substance, in which the antagonistic action results in a series of greys. The discovery, however, of reflex visual sensations no longer necessitates this assumption, since white is the result of equal stimulation of the three fundamental sensations, red, green and violet, whether it be by direct action, reflex action, or by a combination of both which it appears must generally be the case.

Both the Young-Helmholtz and Hering theories recognize that the nature of color vision is essentially trichromatic, the former by supposing the existence of three fundamental sensations, and the latter by the assumption of three pairs of psycho-physical processes. The first theory explains most satisfactorily phenomena, such as those of color mixtures, which arise chiefly from the direct action of light; the second, phenomena relating to color contrast, which have now been shown by Allen to be due largely to the reflex effect of a color stimulus.[20] Each theory therefore is mainly based on only one of the two phases of color perception. In the light of a visual reflex of a sensory nature, the Young-Helmholtz and Hering theories can no longer be regarded as antagonistic. The existence of a reflex, affecting predominantly the complementary sensations, explains fully the apparent antagonism of color sensations, which Hering recognizes as an essential feature of color perception.

This investigation is one of a series relating to the reflex influence of light on the phenomena of color vision, initiated by Prof. Frank Allen, to whom I desire to express my thanks for suggestions and for laboratory facilities placed at my disposal.

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[20] J. O. S. A. & R. S. I. 7, p. 913; 1923.

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VISUAL SENSORY REFLEXES AND COLOR BLINDNESS

BY

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Printed in U. S. A.

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BY [illegible]

SYNOPSIS

Section I contains introductory remarks and the determination of the normal persistency curve of the author in order to determine the character of his type of color blindness.

Section II contains detailed descriptions of the reflex effects produced in the right eye by fatiguing the left with colors of various wave lengths and with white light. The effect of dark adaptation of the left eye upon color sense of the right eye is also studied.

Section III describes the direct effects of fatigue upon the right eye when colors and white light are used. Darkness adaptation of the right, or stimulated eye is also considered.

In Section IV certain theoretical considerations are discussed with special reference to the bearing of the results upon color theory. It is shown that the absence of reflex effects in the retinas is responsible for absence of certain color sensations in the author's [illegible]

The results strongly confirm the Trichromatic Theory of Color Vision and show that in explaining color blindness the assumption of a separate white sensation is unnecessary. The cause of color blindness seems also to be largely connected with the afferent nerve fibers the actions of which are shown to be greatly involved with [illegible] Color Vision.

I. THE NORMAL CURVE

This investigation was undertaken for the purpose of verifying the principle of the reflex enhancement of the visual color sensations recently discovered by Allen.[1] The writer was aware of some abnormality in his color vision, but did not know how much of the spectrum was involved. As the investigation proceeded the full extent of the color deficiency became evident, and advantage was taken of the abnormal condition to study in detail the reflex and fatigue effects of various spectral colors.

The apparatus used was the same as that employed by Allen which was fully described in his paper to which reference has just been made. By the method of measuring the duration of flashes of color at the critical frequency of flicker, persistency curves for the spectrum were obtained, first, when the right eye was in ordinary daylight adaptation, and, second, when it was under the direct or reflex influence of colors. Comparison of the last two types of curves with the normal enabled conclusions to be drawn regarding the action of different colors upon the visual sensations.

The first measurements were made to secure the normal or reference curve with which all others are compared. For this purpose the experiments were conducted in a room lighted by windows so that both eyes were maintained in daylight adaptation. This was necessary since Allen found that darkness adaptation of one eye affected the other in such a manner as to counteract the reflex enhancement of the sensations.

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[1] On Reflex Visual Sensations, J. O. S. A. and R. S. I. 7, p. 583; 1923.

The data for the normal curve are found in Table I together with similar measurements for all the reflex curves described in the next section.

TABLE I. *Reflex Curves*

λ	Normal	White Light	Darkness	Darkness and Pressure	.687μ
	sec.	sec.	sec.	sec	sec.
.74μ	0.0386	0.0423	0.0334	0.0415	0.0421
.72	.0316	.0329	.0293	.0349	.0322
.70	.0266	.0273	.0254	.0280	.0273
.68	.0228	.0229	.0214	.0230	.0217
.66	.0182	.0185	.0178	.0185	.0189
.64	.0161	.0161	.0160	.0162	.0164
.62	.0146	.0150	.0144	.0152	.0145
.59	.0132	.0133	.0130	.0136	.0136
.57	.0130	.0131	.0125	.0133	.0131
.55	.0133	.0135	.0130	.0132	.0132
.53	.0137	.0138	.0135	.0136	.0142
.50	.0163	.0160	.0156	.0158	.0167
.48	.0194	.0189	.0189	.0186	.0187
.46	.0234	.0221	.0225	.0211	.0231
.44	.0295	.0287	.0272	.0276	.0304
.42	.0401	.0358	.0367	.0383	.0401
λ	.660μ	.589μ	.540μ	.450μ	.410μ
	sec.	sec.	sec.	sec.	sec.
.74μ	0.0352	0.0370	0.0383	0.0380	0.0401
.72	.0313	.0300	.0301	.0336	.0345
.70	.0269	.0256	.0258	.0264	.0283
.68	.0238	.0220	.0217	.0234	.0236
.66	.0179	.0185	.0185	.0180	.0203
.64	.0165	.0170	.0166	.0162	.0165
.62	.0147	.0150	.0147	.0149	.0147
.59	.0140	.0135	.0134	.0133	.0136
.57	.0134	.0135	.0133	.0134	.0130
.55	.0137	.0135	.0131	.0136	.0133
.53	.0146	.0143	.0139	.0142	.0135
.50	.0161	.0165	.0168	.0159	.0163
.48	.0194	.0187	.0192	.0189	.0192
.46	.0212	.0214	.0222	.0237	.0233
.44	.0270	.0263	.0265	.0281	.0276
.42	.0355	.0346	.0358	.0401	.0373

In order to discover the extent of the color deficiency or blindness as it is usually termed, the normal of the writer must be compared with one for the eye of a person with normal vision. A similar curve was made on the same spectrum and under precisely the same conditions by W. A. Anderson[2], whose color vision is normal trichromatic except for a short interval of anomalous vision between the wave lengths .61μ and .68μ. The data for this curve are in Table 2.

Table 2.—*Normal Persistency Curve—W. A. Anderson*

λ	D	λ	D	λ	D
	sec.		sec.		sec.
.74μ	0.0301	.64μ	0.0136	.50μ	0.0180
.72	.0249	.62	.0125	.48	.0187
.70	.0199	.59	.0111	.46	.0235
.68	.0158	.55	.0118	.44	.0300
.66	.0142	.53	.0126	.42	.0404

As his color vision is anomalous but not defective, Anderson's curve may be compared with the writer's and thus reveal the extent of the color blindness. The two curves are drawn to the same scale in Fig. 1. The continuous line is Anderson's normal, which in this paper is used only in this figure, and the dotted line is that of the writer. From this figure it is seen that the color vision of the writer is defective from the beginning of the red to the wave length .490μ. The violet portions of the curves coincide, which shows that this sensation is not defective in any way. The writer therefore is shown to be defective in both the red and green sensations. The neutral point is at the wave length .515μ, which is near the point where the two normal curves diverge. It is marked in the figure with an arrow.

In a detailed investigation of color blindness by this method, Allen[3] was able to classify twenty six subjects into seven distinct types or classes: those defective in one sensation only, red, green, or violet, those defective in two sensations, red-green, red-violet, or green-violet; those defective in the three sensations, or the totally color blind. Six of the seven types were found and studied, but only with reference to their normal persistency curves. The missing type was violet blindness

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[2] On Reflex Visual Sensations and Anomalous Trichromatism. J. O. S. A. and R. S. I. 8, p. 731; 1924.

[3] Persistence of Vision in Color Blind Subjects. Phys. Rev. *15*, p. 193; 1902. Also: Persistence of Vision and the Primary Color Sensations. Am. Jour. Physiol. Op. 1, p. 94; 1920.

II. REFLEX CURVES

The first curves to be obtained were the reflex, in which the fatiguing color stimulus was applied to the left eye, and measurements of the critical frequency of flicker were made upon the right eye which remained in daylight adaptation. The curves obtained in this way are compared in the figures with the normal curve of the writer. The differences between the two curves must therefore be due to the effects of color transferred from one eye to the other. Allen[4] found that his reflex curves in all cases were below the normal, showing three depressions in the parts of the curves corresponding to the red, green, and violet colors, which proved that these sensations were always reflexly enhanced in sensitiveness. These effects have been completely confirmed by M. S. Hollenberg,[5] who also worked in Allen's laboratory.

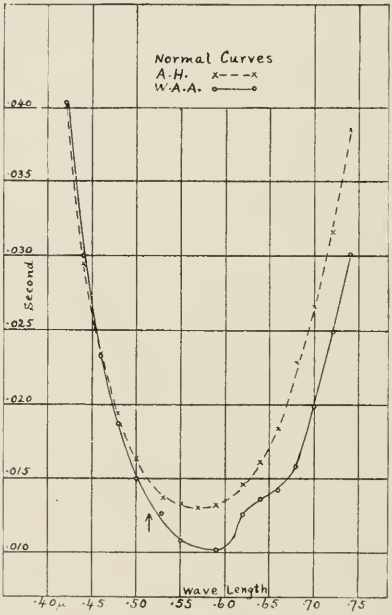

FIG. 1. *Normal curves.*

In no case did either of these observers find that the direct action of light was transferred from one eye to the other in excess of the reflex. Had it been transferred, it would have shown itself, it is presumed, by elevations of the curve above the normal, such as occur in the fatigue and reflex curves in this paper.

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[4] On Reflex Visual Sensations. loc. cit.

[5] On the Verification of the Principle of Reflex Visual Sensations. J. O. S. A. and R. S. I. 8, p. 713; 1924.

In addition to these effects, Allen found six colors .669μ, .572μ, .520μ, .505μ, .480μ and .425μ, which produced neither fatigue nor enhancement, so that the curves coincided with the normal. These were called equilibrium colors.

In the present investigation the red color .687μ was first used as the fatiguing stimulus on the writer's left eye. The curve obtained by the right eye is practically coincident with the normal in the part corresponding to violet, but small elevations occur in the portions of the curve corresponding to red and green. The departures from the normal are so slight that this color may almost be called an equilibrium color for the author. This is quite different from the normal eye, in which the first equilibrium color is .660μ, which lies at the end of the green sensation curves of Abney and of Konig. It may therefore be the case that in color blindness the green sensation curve extends more completely over the red sensation than in normal vision.

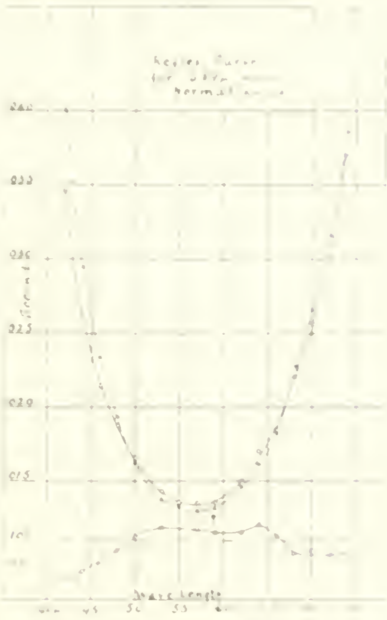

FIG. 2. *Reflex curves for .589μ.*

When the colors .660μ, .589μ, .540μ, and .450μ, were successively employed as fatiguing stimuli, curves similar to that in Fig. 2, for .589μ, were obtained. These are all of the same general type, showing depressions in the red and violet regions and an elevation in the green. The curve for the color .450μ, however, approximates the equilibrium condition. It may be noted also that this color is not far from the point where the normal curves in Fig. 1 diverge, which is considered to mark the boundary between normal vision, and the defective color vision of the writer.

The curve obtained with the violet color .410μ has a depression in the violet and an elevation in the red, with scarcely any effect upon the green.

Almost exactly the same as this is the reflex curve obtained when white light was used as the fatiguing stimulus. This is shown in Fig. 3.

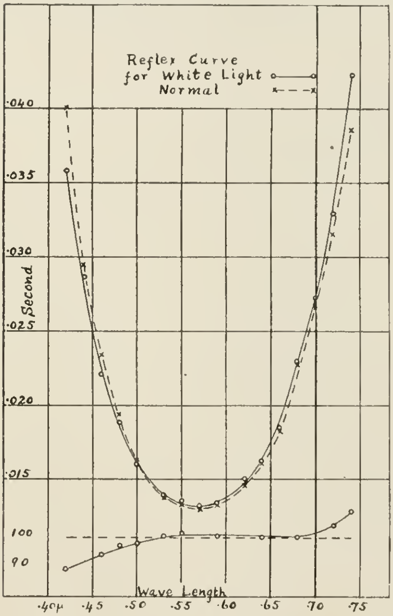

FIG 3. *Reflex curve for white light.*

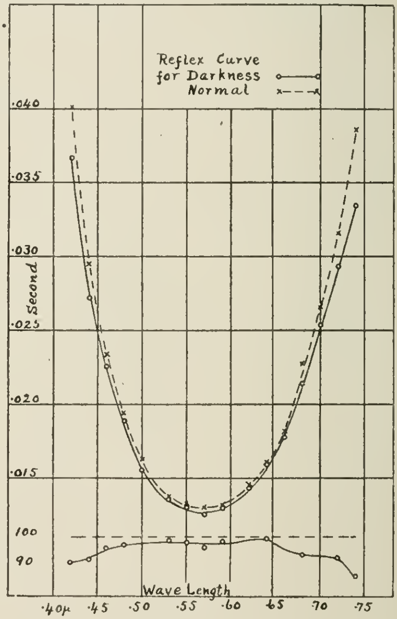

FIG. 4. *Reflex curve for darkness.*

In normal vision, darkness adaptation of the left eye caused the elevation of the whole curve above the normal, showing in consequence that the spectrum became physiologically less bright to the right eye. But in the writer's case, as is shown in Fig. 4, darkness adaptation caused a depression of the whole curve below the normal, indicating enhanced perception of all colors. But when pressure upon the left eye was added to its darkness adaptation, the green and red portions of the curve became elevated.

In Fig. 5 the reduced reflex curves obtained under all the above conditions are gathered together, and their uniformities and characteristics may be readily compared.

It was previously pointed out that the writer's vision was normal as regards the violet sensation. Allen found that in the normal eye reflex action enhanced the three fundamental sensations which depressed the curve in the parts corresponding to them. Since in the eye of the writer the violet sensation is normal, the part of the curve corresponding to it ought to be normal in its behavior and always show a depression. This is the case with all the curves except that for the red color .687μ which is practically coincident with the normal. The violet sensation therefore conforms nearly perfectly with the theory. In four of the six reflex color curves the red portion is depressed and in two cases elevated, but the green is uniformly elevated. In other words, the green sensation always behaves abnormally, while the red is normal in its behavior with four colors in the middle of the spectrum, and abnormal with two which are the extreme red and extreme violet. With white light the violet sensation acts normally, and the red abnormally. Darkness adaptation is abnormal in its effect upon all the sensations. All the curves, however, show the usual threefold division corresponding to the three primary sensations, red, green, and violet. The divisions occur with approximate constancy near the wave lengths .65μ and .50μ, which also is the case in Allen's curves.

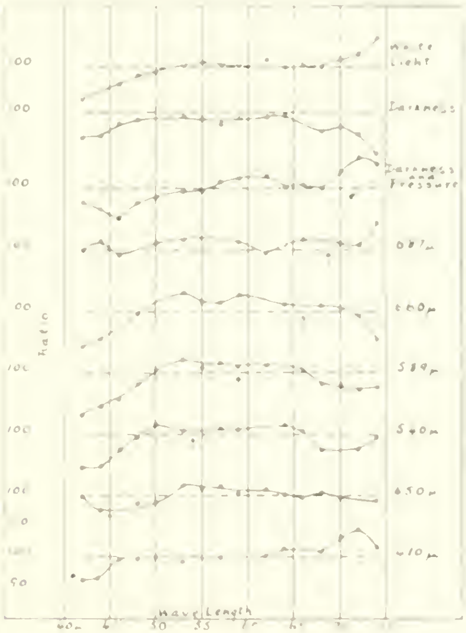

Fig. 5. Reduced reflex curves.

III. FATIGUE CURVES

In Allen's investigations it was found that when the right eye was fatigued with the primary colors red, green, and violet, one elevation was formed in the corresponding part of the curve, and two reflex depressions in the parts corresponding to the remaining sensations. But when the compound colors, orange, yellow, and blue were used, two

TABLE 3. *Fatigue Curves*

λ	Normal	White Light	Darkness	Darkness and Pressure	.687μ
	sec.	sec.	sec.	sec.	sec.
.74μ	0.0386	0.0440	0.0420	0.0440	0.0485
.72	.0316	.0328	.0355	.0372	.0396
.70	.0266	.0275	.0295	.0316	.0316
.68	.0228	.0243	.0237	.0253	.0265
.66	.0182	.0197	.0200	.0200	.0205
.64	.0161	.0165	.0172	.0169	.0170
.62	.0146	.0154	.0147	.0148	.0157
.59	.0132	.0143	.0136	.0140	.0141
.57	.0130	.0141	.0134	.0138	.0141
.55	.0133	.0147	.0136	.0138	.0140
.53	.0137	.0150	.0137	.0140	.0148
.50	.0163	.0160	.0165	.0161	.0170
.48	.0194	.0187	.0187	.0190	.0202
.46	.0234	.0225	.0215	.0230	.0252
.44	.0295	.0297	.0269	.0304	.0306
.42	.0401	.0428	.0366	.0422	.0635
λ	.660μ	.589μ	.540μ	.450μ	.410μ
	sec.	sec.	sec.	sec.	sec.
.74μ	0.0425	0.0396	0.0396	0.0442	0.0390
.72	.0360	.0330	.0350	.0392	.0313
.70	.0297	.0276	.0300	.0329	.0270
.68	.0254	.0238	.0239	.0275	.0223
.66	.0197	.0196	.0193	.0218	.0186
.64	.0170	.0165	.0169	.0173	.0162
.62	.0152	.0144	.0155	.0151	.0144
.59	.0140	.0135	.0139	.0141	.0135
.57	.0138	.0131	.0137	.0141	.0132
.55	.0145	.0136	.0140	.0140	.0133
.53	.0147	.0143	.0143	.0151	.0138
.50	.0168	.0166	.0173	.0173	.0162
.48	.0200	.0196	.0194	.0210	.0191
.46	.0241	.0240	.0232	.0241	.0245
.44	.0305	.0305	.0300	.0320	.0315
.42	.0503	.0465	.0423	.0495	.0430

elevations were formed with each corresponding in position to the two sensations directly affected, and a reflex depression in the remaining sensation. Yellow, for example, fatigues both the red and the green sensations, causing corresponding elevations in the curve, and enhances the violet sensation causing a depression.

The assumption of Helmholtz that all colors directly stimulate all three sensations, though in unequal amounts, was confirmed experimentally by the former investigators, and is most emphatically confirmed by the fatigue curves now to be described. In the normal eye there are always opposite effects produced upon the sensations directly

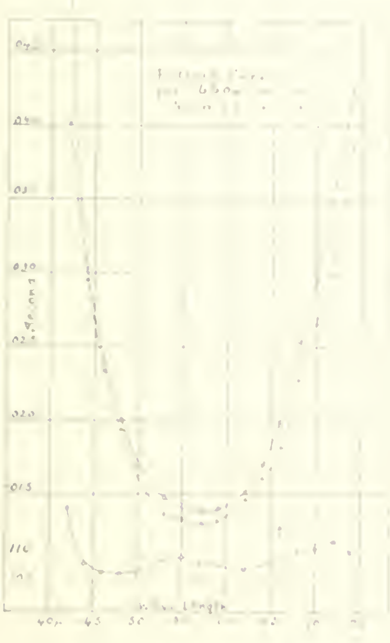

Fig. 6.—Fatigue curve, .600μ.

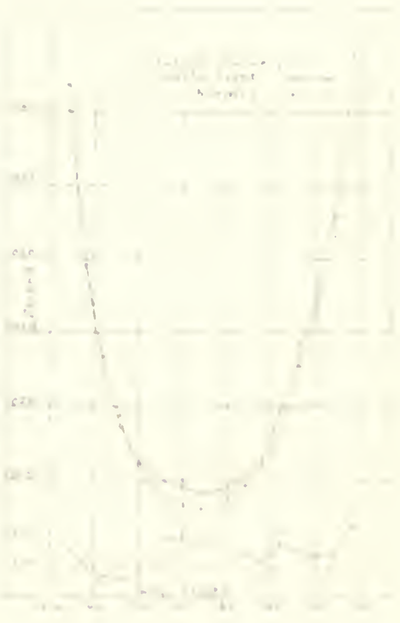

Fig. 7.—Fatigue curve, [illegible]

and those reflexly affected. The two portions of the spectrum thus oppositely influenced are complementary to each other. It will be remembered that these experiments were likewise conducted in a lighted room so that the unused eye was maintained constantly in daylight adaptation.

In the fatigue curves of the writer much the same type of curve is obtained with all the colors used: .687μ, .600μ, .589μ, .510μ, .450μ, and .410μ. The data for these curves are in Table 3, and the curves are similar to that in Fig. 6, for .600μ. It will be noticed at once, especially in Fig. 9 where all the reduced fatigue curves are shown together, that each curve, with the exception of that for the violet color .410μ, is characterised by three elevations in the parts corresponding to red, green-yellow, and violet, the divisions occurring near the same wave lengths as before, .65μ and .50μ. No depression occurs with any of the colors. With the wave length .540μ, the violet elevation is small, while in the case of violet, .410μ, there is an elevation corresponding to that color, and the rest of the curve is almost coincident with the normal. This suggests that this color is not far from an equilibrium point.

When the eye was fatigued with white light, it was found that the curve in Fig. 7 was elevated above the normal, and possessed three elevations. This clearly shows that white light affects the three sensations red, green, and violet.

When the right eye was blindfolded, or in darkness adaptation, the curve shown in Fig. 8 was obtained. This has a depression in the violet region, whereas Allen found his curve to lie above the normal in all parts.

When pressure upon the eye was added to darkness adaptation the writer found that the violet part of the curve was elevated. The three-fold character of the sensations is again clearly demonstrated.

The reduced curves for white light and darkness are also shown in Fig. 9 with the reduced fatigue curves for the various colors.

From the study of the curves for fatigue or the direct action of light, the conclusion is obvious that all colors affect the three fundamental color sensations directly, in accordance with the assumption of Helmholtz. It is also evident that no reflex effects are shown at all. This does not necessarily mean that no visual sensory reflexes exist, but that the direct effects greatly predominate over them.

The identical three-fold character of the curves for white light and darkness constitutes the strongest evidence that these influences act upon the color sensations, and not upon a separate white-black visual substance or sensation as the Hering theory, for example, assumes.

IV. THEORETICAL CONSIDERATIONS

In the study of color blindness it is frequently stated that one or more sensations, or the corresponding photochemical substances, are absent from the retina. Since in color blindness the spectrum is but little shorter than in normal vision, the conclusion must follow that in addition to the color sensations there is a white process also which is responsive to all colors. If, however, all colors stimulate all three primary sensations, in accordance with the trichromatic theory, whiteness is fully accounted for without an additional sensation. Since the evidence adduced in this paper is clear and explicit that all colors act upon all three sensations, the assumption (and it must be remembered that in all theories of Color Vision it is only an assumption) of a separate white sensation or process is needless.

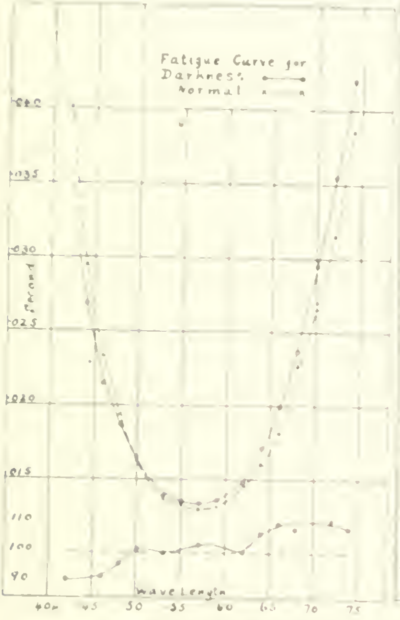

FIG. 8. Fatigue curve for darkness.

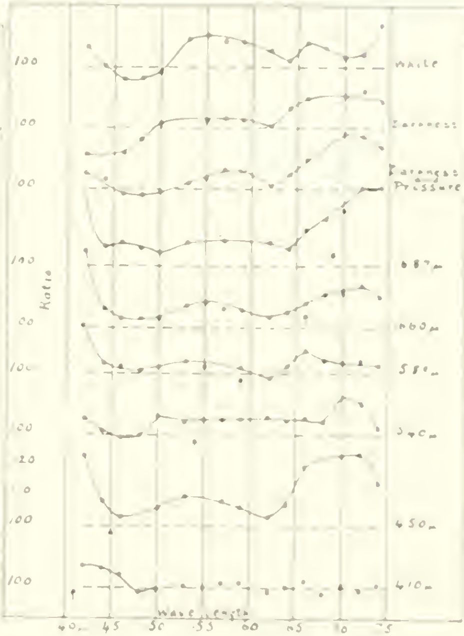

FIG. 9. Reflexed fatigue curve.

There is no doubt that the writer is defective in his color sense, or is color blind in the usual terminology. It is obvious from the curves that the same three regions are affected as in normal eyes. The conclusion therefore follows that in the writer's eye, three color sensations exist and operate. None are missing. But the abnormal occurrence of the elevations and depressions and the complete absence of the latter in the case of fatigue or the direct action of light, show that in color defectiveness or blindness it is the visual reflexes which are chiefly at fault. Hence when light falls upon the eye the counteracting process to fatigue is too small to be effective, though the reflex curves show it is not entirely absent. Though the writer is red green blind in the ordinary sense, yet what he considers to be a red color is perceived after prolonged fixation, if it is quite bright. Also what he calls a greenish image is formed by successive contrast upon looking at a white surface after fatigue with bright red light.

The writer has never been able to obtain any negative after-images either with color or with white light of the strongest character. Even after looking at a bright electric light, no after-images are seen on closing the eyes, except a positive image of the same color for a very brief time. Allen has previously suggested that negative after-images are due to reflex discharges in the efferent nerves, and that positive after-images are due to the persistence of afferent nerve stimulation. The fact that the writer obtained persistency curves at all is evidence that positive after-images are formed in his eyes. But the absence of negative after-images seems to be significantly connected with the absence of reflex effects in the directly stimulated eye. The curves and other characteristics of vision of the writer are all consistent with each other, though they are not normal except as regards the violet sensation.

Since the three sensations are acted upon in two ways, direct and reflex, it might be inferred that innumerable types of color blindness or deficiency should exist. Allen found, as shown in his paper on color blindness previously referred to, that the normal curves of twenty six cases could be readily classified into seven types, to one of which the writer, as shown by his curve in Fig. 1, belongs. The reflex and fatigue curves for several subjects of each type should now be obtained in order to secure sufficient information for a more thorough understanding of these important peculiarities of vision. While generalisation from a single case of color deficiency is perilous, yet it is evident that the curves do give exact information quite consistent with other facts of defective color vision. There appears to be nothing in these experimental results inconsistent with the trichromatic theory of Young-Helmholtz when enlarged by the addition of the visual sensory reflexes. Or we may say positively that the three-fold character of the curves is quite in harmony with that theory of color vision, and indeed strongly confirms it.

These curves show that defective color vision largely arises from disturbances in the efferent fibres of the reflex arc, which suppress the enhancing reflex actions which are essential to normal color vision. In other words, the various types of color blindness are due to inhibitory processes of abnormally large magnitudes acting selectively upon the visual receptors.

This investigation forms part of a series of researches in Color Vision conducted in the Department of Physics of the University of Manitoba with the financial assistance of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa.

I desire to record my thanks to Professor Frank Allen, Director of the Department of Physics, University of Manitoba, for suggestions regarding the interpretation of the curves obtained in this investigation.

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THE REFLEX ORIGIN OF COLOR CONTRAST

BY

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SYNOPSIS

In this paper the principle of sensory reflex action is applied to the explanation of color contrast by the method of Ragona Scina. Abney's experiment in which he found the contrast color induced on a white surface by green to be orange instead of the complementary purple is also explained. Consideration is also given to binocular contrast.

The theories of contrast of Helmholtz, Edridge-Green, McDougall, Mrs. Ladd Franklin, Hering and Sherrington are briefly discussed.

In two papers recently published[1], the writer showed by numerous experimental measurements that every ray of light falling upon the retina produces both direct and reflex effects on the three fundamental sensations, red, green, and violet. The former, or direct action of a color, stimulates and, at the same time, depresses or fatigues the three sensations in very unequal amounts, and is the effect of light or color usually perceived and studied. The latter, or reflex action, enhances the sensitiveness of the three sensations in the retinal area directly excited, in the adjoining regions of the same retina, and is also transferred to the other eye with the same enhancing effect.

The enhancement, while extending to all three sensations, predominantly affects those complementary to the sensations stimulated by the direct action of the color. For example, red light, by its direct action, chiefly affects the red sensation, and to a far less extent the green and violet; by its reflex action it enhances all three sensations, but predominantly the green and violet, which together are the complementary of red.

Since darkness adaptation of the unused eye produces effects that neutralize the enhancement of brightness caused by reflex action, these researches were conducted in a room lighted by ordinary daylight, so that the unused eye was always maintained in daylight adaptation.

This reflex principle, coupled with the trichromatic theory, was shown by the writer to afford a physiological explanation of the modification of lights and colors by contrast. If, for example, contiguous patches of yellow and green colors are viewed by one eye fixated on a point in the junction of the two areas, the yellow light reflexly enhances the sensations producing its complementary, blue, in the retinal area occupied by the green, which is thereby perceived as if it were mixed with blue

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[1] On Reflex Visual Sensations. J. O. S. A. and R. S. I. 7, p. 583, 1923.
On Reflex Visual Sensations and Color Contrast. J. O. S. A. and R. S. I. 7, p. 913, 1923.

Similarly, green enhances its complementary sensations, red and violet, in the area upon which the yellow light falls, causing that color to appear as if mixed with purple. Thus each color is perceived as if mixed to a greater or less extent with the complementary of the other, an effect which in general gives them the appearance of being moved away from each other in the spectrum. Two colors which are complementary will obviously be modified chiefly by having their saturation deepened or increased.

It should be noted, however, that the complementary effect of contrast is only a predominant action, for the visual reflex enhances all three sensations.

It is to be expected therefore from the reflex principle that slight departures from the complementary character of contrast will always occur. This is well recognised by color theorists, as Parsons[2], for example, shows in his statement that "under ordinary circumstances the induced color is not the precise complementary of the inducing, as was known to Goethe, and has been fully investigated by Hering."

In the former paper on contrast to which reference has been made, several of the most illustrative examples ofcontrast phenomena were discussed and explained by the new reflex principle. In this communication some additional contrast experiments of various observers are considered and the reflex theory also applied to explain them.

One of the most effective modes of obtaining contrast is that devised by Ragona Scina. For some time the writer found difficulty in reconciling this contrast effect with the explanation on the reflex principle. Rood[3] has described this important method in such detail that the writer ventures to quote from him.

"Two sheets of white cardboard are attached to a couple of boards fastened together at a right angle, as indicated in Fig. 1. Between the boards a plate of rather deeply coloured glass, G, is to be held at an angle of 45°. If the eye is placed at E, two masses of light will be sent to it. From the vertical cardboard white light will start, and, after being reflected on the glass plate, G, will reach the eye. This light will be white, or almost entirely white, since it is reflected from the upper surface of the coloured glass plate. The second mass of white light will proceed from the horizontal sheet of cardboard, H, and after traversing the plate, G, will become coloured by absorption. If the glass plate is red, this light when it reaches the eye will of course have the same colour; consequently the first result is that we have presented to the eye a mixture of red with white light, which will give the observer the idea that he is looking at a horizontal, square field of a somewhat pale reddish tint. If now a small black square be attached to the vertical cardboard at B, of course no white light can come to the eye from this portion of the cardboard and the image of this spot will seem to the eye to be at *b* on the horizontal board under the eye. Under ordinary circumstances this image would appear black, in point of fact, however, in this case it appears deep red, owing to the red light transmitted by the plate of glass. Thus far the arrangement amounts to a device for presenting to the eye a mixture of red with white light, the white light being absent at a certain spot, which consequently appears of a deeper red. A similar black square is now to be placed on the horizontal board at C; it will of course prevent the light from the place it covers from

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[2] Colour Vision. p. 128; 1915

[3] Colour or Modern Chromatics, 3rd Ed., p. 257.

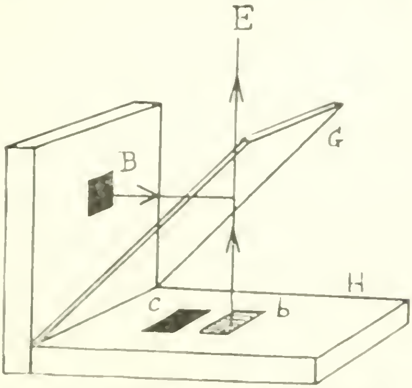

Fig. 1. *Contrast method of Ragona Scina.*

reaching either the red glass or the eye, and under ordinary circumstances would be perceived simply as a square black spot. Owing, however, to the fact that the upper surface of the glass plate is reflecting white light to the eye, it really appears as a grey spot. The final result is that we present to the eye at E a pale red ground on which is a spot of pure grey, and near it one which is deep red. Owing to contrast, however, the appearance is different: instead of a grey spot we see one strongly coloured green-blue. This effect is partly due to contrast with the pale red of the ground, but still more to the presence of the deep-red spot. This latter we can remove by taking away the black square, B, which diminishes the effect considerably. But now comes the most curious part of this experiment; if we select a square of grey paper which has the same colour with the grey square seen in the apparatus, apart from the effects of contrast, and place it *over* the glass plate and near the other two images, it will not be affected in colour, or only to a slight extent. In point of fact, we now have, *side by side*, on the same field, two grey squares quite identical in actual colour, but one appears by contrast blue-green, while the other is not affected, but is perceived by the eye as being simply a square of grey paper. *As soon, however, as* the observer recognizes the fact that these two squares really have the same grey colour, the illusion instantly vanishes, and both of them remain persistently grey. It is evident that in this case, as with coloured shadows, the judgment is at fault rather than the retinal nerves; for *as soon as* an opportunity offers, it corrects itself and takes a new departure. The illusion in this case, as well as with the coloured shadows, is produced quite independently of the knowledge of the observer, who may indeed be a trained physicist, minutely acquainted with the facts of the case, and with all the details employed in producing the deception, and still find himself quite unable to escape from its enthrallment."

In order to understand the reflex actions involved in this experiment we must consider the complete color pattern on the retina. This consists of a pale red ground over the retinal periphery where it excites but little reflex effect, since its physiological intensity rapidly diminishes as the distance from the centre is increased.[4] In the central retina are three fairly large areas, one, a deep red, and two grey of equal intensities which, according to Rood's description, are "side by side". The greatest part of the contrast effect on the grey, as Rood points out, is due to the deep red patch, which is naturally brought about by directing vision between the red and grey areas.

In accordance with the reflex visual process outlined above, the red light enhances the sensitiveness of the three primary sensations, red, green, and violet, in the surrounding areas of the retina, but predominantly the sensations complementary to red. The white light from the grey patch falling upon the unequally excitable sensations, stimulates the green and violet more than the red, which results in the production of the bluish-green color observed.

The critical part of the experiment is contained in the words of Rood which the present writer has italicized in the quotation, particularly the expression: "*As soon as* the observer recognises", etc. Expressed in other words, this part of the description means that when vision is fixated on a point between the two *grey* squares, the image of the large red area then falls on the periphery of the retina, where its intensity and consequently its reflex effect are greatly reduced; and, as the words of

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[4] Parsons: Colour Vision, Fig. 24, p. 69; 1915.

Rood imply, a *time* interval is allowed for the two grey areas to readjust their retinal actions, and for the reflex effect of the deep red or salmon. As both greys are originally made of equal and low intensities, their reflex effects on each other are negligible. When the color contrast is reduced to a minimum, the experiment is resolved mainly into one on luminosity contrast.

In attributing this effect to illusion or deception of the judgment, Rood remarks again that it corrects itself "as soon as an opportunity offers". This expression also implies an interval of time, which in some contrast experiments is quite necessary.

It is probable, however, that careful observation will show both grey patches to be slightly tinged with the contrast green-blue color by reflex action of the surrounding pale red ground.

The ascription of Seina's contrast effects to deception of judgment is therefore an erroneous interpretation. The reflex principle not only nullifies the psychological theory of Helmholtz but also supplies a positive physiological action quite adequate to explain the phenomena.

The last sentence of Rood's description in which he remarks how even a trained observer "minutely acquainted with all the details employed in producing the deception", is quite unable to prevent himself from being deceived, is a strong tribute to the clarity and precision of the judgment in rendering a truthful verdict on the various actions and reactions involved in the experiment.

Abney[7] has described some observations on simultaneous contrast which, on first consideration, also appear contradictory to the action of the reflex principle.

In his work he used a white surface upon part of which fell a beam of light of any desired spectral color, and upon the contiguous area a bright white light from an electric arc, or from an Argand burner.

By this experimental arrangement he desired to determine the contrast color induced in the white area by the color on the adjoining surface. He found that the contrast color in all cases could be matched by a single spectral color when diluted with white light. He noted, however, that the induced color was not always the complementary of the active light. It was found, for example, that when green is the active color, the induced color upon the white surface is orange instead of purple, which is the complementary of green.

The contradiction, however, is only apparent, as further considera-

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[6] Researches in Colour Vision, p. 121.

Proc. Roy. Soc. 56, p. 221, 1894.

tion shows. The reflex effect of green light when it falls upon one retinal area enhances the sensibility of the complementary sensations in the adjoining areas. A purple color is therefore induced in effect upon the part of the retina receiving the image of the bright white light. Now purple is formed by excitation of the red and violet sensations, of which red is much the more prominent or effective. It is also well recognized that colors mixed with white light tend towards yellow. Abney himself says:[6] "In the red the colour becomes pinker as more of the white light is added, the scarlet becomes orange, the orange yellow, and the yellow green. The yellow-green does not suffer a change but as the green is approached it becomes yellower in hue. . . .as the violet is approached a very small quantity of white will make it appear nearly salmon-coloured. If the white light added be that of a paraffin lamp, the red became more orange, the scarlet, as before, orange. . . . "

By referring to the reflex color curves[7] of the present writer, it will be seen that when white light is used as the stimulus, the yellow-green part of the spectrum is conspicuously enhanced in brightness, an effect which is doubtless explanatory of the latter observations of Abney. The dilution of a color with white light can only mean that the three primary color sensations are directly stimulated in certain, probably equal, proportions by the white light, and simultaneously in other proportions by the color. The net result of all the stimulations is finally interpreted by the judgment as a modification of the original color. Abney's observations show a few of such changes in the hues of spectral colors.

If in Abney's contrast experiment purple light had been allowed to fall upon the bright white surface, the change to orange would have been immediately recognized as conforming to established principles. But white light formed by a mixture of all waves may become colored in two ways: first, by adding light of the desired color, second, by selectively enhancing the sensibility of the proper sensation or sensations by reflex action thereby compelling the waves of the color already in the white light to excite these color sensations to a much greater degree than the remainder. The purple color may be obtained by adding a suitable mixture of red and violet light, or by increasing the sensibility of the corresponding sensations. In Abney's experiment the latter is the mode employed. The sensation of purple is formed by the enhanced excitability of the red and violet sensations, due to the reflex action of green, and it is simultaneously changed to orange by the characteristic modifying power of white light due also to reflex action.

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[6] Researches in Colour Vision. p. 255.

[7] "On Reflex Visual Sensations"—loc. cit. p. 598.

There is therefore no conflict between Abney's contrast experiments, when completely analysed, and the explanation afforded by the application of the principle of the visual sensory reflex. We may indeed go further and say that in Abney's apparently contradictory experiment we have a most unexpected confirmation of the reflex principle in conjunction with the trichromatic theory.

In the paper by the writer "On Reflex Visual Sensations"[8] it was shown that the reflex effect of color stimulation of one retina was transferred to the other so as to produce enhancement of the sensibility of all three primary sensations, but predominantly of the complementary of the original color stimulus. It was then stated that this effect accounted for binocular contrast.

The usual experiment on binocular contrast found in works on color vision, is that of Hering, which is thus described by Luckiesh[9]. "Hering devised a most striking demonstration of binocular contrast. Red and blue glasses were placed in front of the two eyes respectively. The glasses sloped away from the eyes from the nasal to the temporal side. This permitted a control of saturation by introducing a white image from the sides by reflection. A black stripe on a white ground is doubled by increasing or decreasing the ocular divergence. The observed ground appears spotted, alternately blue and red, and sometimes a purplish white, which is due to retinal rivalry. The stripe seen through the red glass appears green and through the blue glass appears yellow."

When this experiment is analysed, however, it appears to have nothing to do with binocular contrast, but consists of two different experiments on uniocular contrast proceeding simultaneously.

Let us consider the retinal pattern formed by the eye with the red glass in front of it. The white light from the ground surrounding the black stripe passes through the red glass and produces upon the retina a red image with a black area in the central part. The red light by reflex action enhances the sensitiveness of the three sensations, red green, and violet, but predominantly the two latter in the dark area. The white light from the side source, reflected by the surface of the red glass upon the retina, renders the red ground less saturated, and stimulates the green and violet sensations more than the red in the dark area, which therefore appears green or bluish-green in color.

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[8] Loc. cit. p. 615.

[9] Colour and its Applications, p. 177.
See also: Burch, Physiological Optics, p. 86.

Similarly in the other eye, the blue ground color predominantly enhances the excitability of the sensations producing the complementary yellow in the dark area, so that the white light from the side source causes that color to be seen.

Nothing in these effects therefore appears to differ from ordinary contrast, so that binocular contrast need not be invoked to explain the observations. Indeed each of the two experiments appears to be identical with the color contrast part of Ragona Scina's experiment which has been described above.

Probably each eye does affect the other to some extent; but the more powerful uniocular actions conceal the binocular from observation.

Myers, in his work on Psychology[10], correctly refers Hering's experiment to uniocular contrast, and in addition has described an undoubted binocular contrast effect. "By fixating a nearer point, the student produces double images of a white stripe on a black background. He places a red glass before the one eye and an equally bright grey glass before the other. He observes if the image seen through the grey glass is tinged with green (the complementary colour to red). He then removes the red glass and observes that the image yielded by the eye which has been covered with the grey glass, becomes a well-marked red."

These effects may be explained as follows. The red light in one eye reflexly enhances all three sensations in the other, but more especially its complementary. The white light coming through the grey glass first stimulates the green sensation in excess of the others and proportionately fatigues it, but acts upon the red sensation to a much less degree. When the red glass is removed the selective enhancement of the sensations no longer operates, and the white light then excites the red sensation more than the others, since it has been less fatigued.

In uniocular contrast a similar phenomenon is observed to which a similar explanation applies, except that two areas of a single retina are involved instead of the two eyes. To quote Myers[11] again: "But these effects (complementary) of simultaneous contrast disappear on prolonged fixation and are replaced by others of a directly opposite character. The surface, which at the beginning of fixation had evoked a contrast colour or brightness, now induces its own colour or brightness. This is termed simultaneous induction."

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[10] Text-Book on Experimental Psychology, Part II.
Experiments 133 and 131, pp. 87 and 86; 1923.
See also: Schafer, Text Book of Physiology, *2*, p. 1098; 1900.

[11] Loc. cit. Part I. p. 76.

In passing we may refer to two other binocular phenomena. In the words of Myers[12]: "We have yet to explain why a steady image is able, while a flickering image is unable, to affect the image of the corresponding area of the other eye." And: "The brightness of the combined image of two steady flickerless lights respectively thrown on corresponding retinal areas, is obviously not equal to the sum of the two brightnesses. Its value is usually slightly above the arithmetical mean of the brightness of the uniocular components, provided that these do not differ too widely from one another. When the components are equally bright, the binocular increase has been variously estimated to be from one-tenth to one-thirtieth."

The reflex curves of the writer[13] show that the reflex effect of light transferred from one eye to the other, causes enhancement of the brightness, except when the light is dim, in which case the brightness is diminished. But time is an essential factor in producing results to a measurable degree. The separate flashes of a flickering light in one eye have too little time in which to enhance sufficiently the brightness of the light in the other. Another effect also must not be overlooked. Darkness adaptation of one eye diminishes the brightness of light in the other. A flickering light produces intervals of darkness alternating with light, and the two effects nullify each other. Therefore both phenomena noted by Myers are in conformity with the reflex principle.

It has long been known that white tissue paper spread over the two contiguous color areas accentuates the contrast effect. This admits of easy explanation by the reflex theory. Each of the two contrasting colors enhances its complementary sensations in the area of the retina occupied by the other. Both colors stimulate their own sensations, and to a limited extent the enhanced sensations as well. The tissue paper, however, reflects upon the active retinal areas a small amount of white light which contains all the colors of the spectrum. An additional stimulus for each enhanced sensation is thereby provided, and the reciprocal modification of the colors is rendered much more effective and complete. In general, the same function is performed by any mode of reflecting white light into the eye so as to cover the areas of the contrasting colors.

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[12] Loc. cit. p. 270.

[13] J. O. S. A. and R. S. I. 7, p. 583, 1923.

Contrast is a phenomenon of such fundamental importance that every theory of Color Vision must offer some explanation of it. And it is precisely this phenomenon which taxes the resources of every theory to the utmost degree.

In elaborating the trichromatic theory of Young, Helmholtz found it necessary to abandon the physiological actions entirely in regard to contrast, and therefore introduced the psychological theory of the systematic deception of the judgment. Many writers have shown the inadequacy of this explanation for uniocular contrast, and Myers[14], referring to binocular contrast, gives the conclusive objection that "one can hardly suppose that unconscious inferences arising from previous knowledge can be carried so far as to lead simultaneously to two different errors."

Edridge-Green[15] considers contrast at considerable length, and says: "My conclusion, therefore, is that the contrast colour developed in simultaneous contrast is due to the perception of an actual objective relative difference—in fact, the greatest difference which is perceptible in the circumstances, white being not a fixed objective quality, but a sensation produced by admixture of light of certain wave-lengths."

The writer is unable to grasp the meaning of this statement with sufficient clearness to apply it to any experiment on contrast. It appears, however, to regard contrast phenomena as purely psychological in their origin.

The color theory of McDougall "attributes simultaneous contrast to the inhibitory action of a given cortical visual process upon the visual process in the neighboring cortical regions."[16] If, for example, a grey surface with a red area upon it be fixated, the "highly excited activity of this red area depresses the activity of the red apparatus in the neighboring grey area of the cortex, whereby the blue and green in the latter area predominate over the red apparatus. . . .It is owing to this supposed inhibition of the red that the blue-green colour is produced."

If, however, the red is inhibited its brightness will be destroyed or diminished, while the blue-green will retain the same intensity as at first. But the experiments of the writer show definitely that, when bright, all colors are reflexly enhanced in brightness, and therefore no inhibitory process can be operative under these conditions. Many

[14] Loc. cit. p. 93.

[15] Physiology of Vision, p 244.

[16] Myers: loc. cit. Part I, p. 94.

contrast experiments also are in harmony with this, and show a distinct brightening of the colors contrasted. But with contrast darkening effects, which also are known, it is quite apparent that inhibition does occur. In these cases the sensory reflex arc would be suitable, and probably necessary, for that purpose. The theory of McDougall in this respect may therefore be partially correct; but the inhibition of color under certain conditions is not at variance with the reflex principle, but rather confirms it.

Mrs. Ladd-Franklin offers a theory[17] of contrast which is highly mechanical and appears to involve quite impossible features. According to it the first color sensations were yellow and blue, which originated by differentiation of some of the primitive grey-molecules into color molecules. In process of time the yellow molecules became further differentiated so as to be sensitive to action by waves of red and green.

In order to explain simultaneous contrast it is supposed, for example, that a red light will deprive large numbers of the color molecules of their red constituents, thereby leaving them partly mutilated and very unstable. The partially disintegrated molecules, however, still retain their green and blue constituents. These are swiftly conveyed in large numbers into the surrounding retinal areas where "their complete destruction causes the phenomenon of simultaneous contrast."

Parsons regards this explanation of contrast as unsatisfactory largely for the reason that the retinal circulation conveying the mutilated molecules would have to be "almost instantaneous" over large areas to accomplish the purpose, and no such circulation is known to exist.

Since two contrasting areas of color modify each other, there must of course be two circulations in opposite directions. In general there must be as many circulations, or as many directions of the circulation, as there are contrasting colors in the field.

It is obvious that binocular contrast cannot be explained on this theory. No transfer of material particles from one eye to the other is possible.

The theory is unsatisfactory for another reason, since the assumed mechanism upon which the whole theory depends, is by its nature removed beyond the limits of experimental inquiry.

The theory of Hering may be summarised sufficiently for the present purpose by quoting from the description given by Myers.[18] "Hering assumes that there are two elementary systems, one of which gives rise to red and green, the other to yellow and blue sensations, and that there is a third apparatus, excitation of which gives rise to the colourless series of sensations. According to this theory, the physiological actions of a colour stimulus and of its complementary colour stimulus are antagonistic. Red, for example, causes a katabolic (or dissimilation) change in the red-green apparatus, yellow a like change in the yellow-blue apparatus; green causes an anabolic (or assimilation) change in the former apparatus, blue a like change in the latter. The sensation of orange results from katabolism in the red-green and the yellow-blue apparatus, that of purple from katabolism in the former combined with anabolism in the latter apparatus.

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[17] Parsons: Colour Vision, p. 273; 1915

[18] Loc. cit. p. 88

"Each apparatus always tends to recover equilibrium, upon removal of the stimulus. After the red-green apparatus has been made to undergo dissimilation owing to the 'allonomous' action of a red stimulus, it proceeds to return to equilibrium by an 'autonomous' process of assimilation thereby developing the complementary after-sensation of green. Thus one colour sensation automatically evokes the opposite or complementary after-sensation.

"Hering explains the effects of simultaneous contrast by a similar principle. He supposes that the process of assimilation, set up by a stimulus in one part of the retina, brings about a process of dissimilation of the same apparatus in neighboring parts of the retina."

But what is the process or physiological mechanism by which an effect in one part of the retina brings about its opposite in another? Obviously, retinal circulation, diffusion, or a process of conduction, like heat conduction for example, cannot be operative, as they would have to be almost instantaneous in their action. Further it is not the same, but an opposite effect that the stimulated area of the retina induces in the surrounding regions.

Since the phenomena of binocular and of uniocular contrast are similar, the same explanation must apply to both. Hering's theory that a direct color process in one area of the retina automatically gives rise to an opponent complementary effect in the surrounding regions, must, therefore, if correct, include the same effect in the other eye as well. Hering assumed that dissimilation brings about assimilation of the photochemical substances, but did not show how it was done. As his theory stands, it fails to account for binocular contrast. But the principle of visual sensory reflex action renders it clear how areas in one as well as in both retinae, reciprocally affect each other. The reflex nervous impulses, with enhancing power upon the sensations, travel back from the visual centres in the same time to all parts of each retina. Whether their effect on the visual receptor organs causes assimilation of some substance remains to be proved. Concerning this part of Hering's theory, the writer has no experimental evidence to offer. It may be suggested, however, that the reflex impulses acting on the receptor organs may produce a condition of selective instability in the photochemical substances so that certain waves may thereby be more effective than others in producing visual stimulation.

Sherrington[19] concluded from his extensive experiments on the binocular fusion of visual sensations and related phenomena that "only after the sensations initiated from right and left 'corresponding points' have been elaborated, and have reached a dignity and definiteness well amenable to introspection, does interference between the reactions of the two (left and right) eye systems occur. The binocular sensation attained seems combined from right and left uniocular sensations elaborated independently." The further conclusion follows that binocular contrast and Fechner's paradox are due to a central mechanism where the separately elaborated retinal sensations are fused with consequent modification of their hue or brightness. With these conclusions the experiments of McDougall appear to be in accord.

The view advanced by the present writer is that a stimulus acting on one retina modifies the corresponding area of the other by enhancing or depressing the sensitivity of the visual receptors. This, it was suggested, is accomplished by a sensory reflex operating through a central mechanism.

Since it is found that uniocular contrast is similar to binocular, and that it is due to the same process, it follows that Fechner's paradox should also occur when two adjacent areas of a single retina are employed.

It is interesting and suggestive to note that Sherrington[20] also states that "The 'immediate spinal induction' exemplified by reflexes has a counterpart in visual irradiation. Visual contrast, if translated into terms of reflex contraction, bears close resemblance to 'successive spinal induction'. The features of fatigue repeat themselves in both sets of phenomena."

The increased sensitiveness of the sensations by reflex influence is apparent almost immediately after the direct stimulation begins. But since fatigue or depression of sensitiveness also accompanies the direct action of color, a longer interval of time is required for the two actions to reach some condition of equilibrium. During this period changes in hue or brightness of a color will be observed, as the three sensations approach equilibrium in unequal times. In this way we may explain the changes in color which occur with time of fixation. When the direct action of light ceases, the reflex discharge may continue, and so produce the complicated series of negative after-images. This subject is too involved for present consideration. But it may be suggested generally that positive after-images are due to impulses which reach consciousness through stimulation of the afferent nerves; negative after-images are due to nerve discharges in the efferent portion of the reflex arc.

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[19] Integrative Action of the Nervous System, p. 381.

[20] Ibid. p. 387. See also p. 208.

An effective conclusion to this paper may be found in the following remarks of Myers.[21] "The close resemblance of binocular to uniocular contrast compels us to suppose either that colour sensations are of more central origin than is commonly believed, or that a direct nervous connection exists between the two retinae whereby stimulation of one eye leads to retinal changes in the opposite eye. Such nervous connection has been demonstrated. Further, we know that movement of the cones, produced in one eye, leads to cone movement in the opposite eye. But this reaction is too slow to explain the immediacy of binocular contrast. It has been suggested that the electrical variation in the two eyes, which is known to occur after uniocular stimulation, may be the physiological basis of binocular contrast."

Further (p. 100), "Nothing is more certain than that, in addition to the more peripheral processes, central processes are also involved, in elaborating visual sensations. But at present we are powerless to separate the one from the other; we can only speak of changes in one vast unravelled complex,—the cerebro-retinal apparatus."

The nature of a visual sensory reflex arc involves central processes in Color Vision, one effect of which is the enhancement of the primary sensations in the retina. In this and other papers the writer has endeavoured to show that it is now possible to separate or distinguish the direct from the reflex actions of color, and so, it is hoped, to proceed one step farther in the unravelling process to which Myers alludes.

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[21] Loc. cit. p. 268

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ON THE TACTILE SENSORY REFLEX. By FRANK ALLEN and A. HOLLENBERG. From the Physics Department, University of Manitoba. (With six figures in the text.)

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ON THE TACTILE SENSORY REFLEX. By FRANK ALLEN and A. HOLLENBERG. From the Physics Department, University of Manitoba. (With six figures in the text.)

(*Received for publication 1st May 1924.*)

SYNOPSIS.

IN this communication a description is given of the method of studying the tactile sensation by measuring the critical frequency of percussion of air pulses when they become fused into a continuous sensation. By applying the method to the index finger of the right hand, a normal curve is obtained for a range of air pressures from 1·0 cm. to 5·0 cm. of mercury. The measurements show that there are two fusion points of intermittent stimuli, which are designated superficial and deep touch. By plotting the time values of the critical frequency of percussion against the logarithms of the air pressure, the curves become straight lines conforming to the equation $D = -K \log P + C$. Each curve consists of two straight lines of different slope, which are analogous to similar effects in light and sound perception. In light the effect has been attributed to rod and cone vision. It is shown that it must be referred rather to some property that all sensory nerves possess in common.

The effect of fatigue upon the critical frequency of percussion was measured, and its curve was found to lie above the normal but exactly similar to it. This is also the same as in light and sound.

Reflex enhancement of the tactile sensation was produced by tightly bandaging the third digit while the critical frequency of percussion was measured for the index finger. The measurements showed that the enhancement curve lies below the normal, similar to the effect produced in one eye by fatiguing the other. Reflex enhancement from the other fingers was also obtained with like results. Similar effects were obtained for both first and second fusion points.

The curves for each fusion point converge and intersect at what is termed an "equilibrium pressure," where reflex and fatigue effects appear to vanish.

The presence of direct fatiguing (afferent) and reflex enhancing (efferent) effects in the tactile sensation is applied to tactile contrast and after images; WEBER's law is discussed and shown to be the difference between two opposing physiological processes whose laws are unknown.

The principle of the sensory reflex is used in discussing sensory tone, WATERSTON'S principle of fluctuation of sensory response, and the phenomena of itching and tickling. Attention is directed to the probable analogous pain reflexes by which referred pain may be explained. The possibility of antagonistic sensory reflexes is also discussed.

THE NORMAL CURVES.

This investigation is an extension to the sensation of touch of the recent researches of one of the authors,[1] which brought to light a new phenomenon in the domain of the receptor end-organs concerned in vision. In two papers it was shown by many experiments that when an area of one retina is stimulated by light, the surrounding areas as well as the other retina become reflexly affected, so that the threshold of stimulation of those receptors is lowered and their sensitiveness enhanced. In the actual receptors stimulated it was further shown that there are in constant operation opposing actions between the direct fatiguing force and the enhancement brought about by the reflex process, between which the receptors are always in a state of equilibrium.

This discovery to a very great extent can be attributed to the method of study, which is the utilisation of the critical frequency of flicker as a measure of the sensitiveness of the retinal receptors. Though periodic interruption of external stimulation has been employed for many centuries, especially in vision, it has not been realised until lately that fundamentally it is an accurate method of determining the sensitiveness of receptor organs generally. When in the case of light the retina was fatigued, the critical frequency of flicker was diminished below the normal rate, and when the sensations were enhanced, it was increased above the normal. By comparing the frequencies measured when the retina was in the normal, fatigued, and enhanced conditions, the state of the visual receptors could be determined with precision.

The same method of study has also been applied in our laboratory to the investigation of problems in the perception of sound.[2] By means of interrupting a ray of sound the critical frequency of pulsation or flutter of tones was measured when the ear was in its normal and afterward in a fatigued condition. The peculiarities induced in the auditory mechanism by fatiguing it with definite tones were elucidated, but the apparatus was not well adapted to the detection and measurement of reflex effects. These were therefore left for future investigation by improved experimental conditions.

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[1] ALLEN, "On reflex visual sensations," Journ. Op. Soc. Amer., 1923, vii. 583; "On reflex visual sensations and color contrast," *ibid.*, 1923, vii. 913.

[2] "On the critical frequency of pulsation of tones," Miss M. WEINBERG and F. ALLEN, Phil. Mag., 1924, xlvii. 50; "On the effect of aural fatigue upon the critical frequency of pulsation of tones," Miss M. WEINBERG and F. ALLEN, *ibid.*, p. 126; "On the effect of fatiguing the ear with combinations of two or more tones," M. WEINBERG, *ibid.*, p. 142.

So successful was this method of studying the state of receptivity of sensory end-organs in these senses, that it was decided to extend it to the tactile sensation. Up to the present time the chief means of measuring the tactile state of the skin was the use of glass-wool fibres attached to wooden handles, and by their means the force of the liminal stimulus was determined.[1] This device had a very limited range of usefulness, which was exhausted when the different parts of the integument of the body were compared and classified in the order of their sensitiveness.

Our idea was to use interrupted stimuli upon some part of the skin, and to determine their rapidity when the separate sensations became fused into continuity. In light a similar phenomenon is called the critical frequency of flicker, and, as just remarked, the corresponding phenomenon in sound is called the critical frequency of pulsation or flutter of the tone. So in the tactile sensation the same peculiarity may appropriately be termed the critical frequency of percussion.

Considerable difficulty was experienced at first in finding a means of stimulating the skin interruptedly, and at the same time measuring the force of each stimulus. Obviously no solid point of stimulus could be used, for it would be almost impossible to measure the force of impact and always to obtain constant conditions. The difficulty was finally overcome by employing air under pressure as the means of stimulation. The advantages of employing a jet of air as a source of interrupted stimulation are: first, its pressure can be definitely controlled and accurately measured by a mercury manometer; second, it is elastic, and, after striking the skin, it rapidly effuses into the surrounding air; third, the pressure with which it strikes the skin, when the latter is at a constant distance from the nozzle, is directly proportional to the pressure in the manometer.

To interrupt the air-stream a disk 8 inches in diameter was made, with twelve equal openings separated by the same number of interspaces of equal width, each subtending an angle of 15° at the centre of the disk. This was rotated by a small electric motor (D.C.) whose speed was regulated roughly by a rheostat, and more accurately by a leather brake, in order to adjust it to the point where the intermittent sensations became just continuous. By means of a speed counter attached to the motor every fiftieth revolution was electrically recorded on a chronograph, together with half-second intervals from a clock. Thus we have the data for evaluating the duration of a single stimulation at the critical frequency of percussion. From analogy with light we may conclude that in both auditory and tactile sensations this time interval measures the duration or the persistence of the positive after-image in undiminished strength.

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[1] Starling, "Human Physiology" (3rd ed.), p. 630; C. S. Sherrington, in Schafer's "Text-book of Physiology," 1900, ii. 927.

The part on which it was decided to study the effect of intermittent stimuli was the skin on the volar aspect of the terminal phalanx of the index finger of the right hand. This part was selected because, as judged by the needle method previously referred to, it is the most sensitive part next to the tongue, nose, and lips, and also because it is the part most easily applied to the instrument of measurement.

In all the experiments about to be described, the nozzle from which the air issued was 1·5 mm. in diameter, and the distance from its tip to the skin of the finger was always 2·3 cm. This distance was chosen because it happened to be the shortest distance within which the disk could rotate with safety. The nozzle was directed so that the air jet was perpendicular to the plane of the disk and to the stimulated area of the finger. A suitable stand was made on which the ulnar edge of the hand could rest while measurements were made upon the finger.

In making readings a constant routine was followed. First, the finger was rested for about ten minutes, during which nothing was touched by it. Then the air pressure was adjusted to the desired amount by the left hand. The right was then placed on the stand provided, in the position just described. The index finger was placed in position opposite the nozzle and the disk set in rotation. Its rate was accurately adjusted by means of the rheostat and brake, which were operated by the left hand. These adjustments occupied from fifteen to twenty seconds. When the critical point of fusion of the stimuli was reached, the chronograph was started by a foot pedal. By means of the brake, the left hand maintained the speed of the disk exactly at the critical point. The mercury manometer was kept in view so that any variation of pressure which might invalidate the reading could be detected. From the chronographic record the time interval of a single stimulus, or the duration of the sensation in undiminished strength, was then evaluated. From two to four such readings were made for each pressure, and the mean of these was taken as the final result.

It should be remarked that one cannot obtain consistent readings with this method at the outset. It requires a great deal of patience and training before accurate readings can be made. One of the authors was for a time compelled to block his ears, because the fusion of the interrupted sound of the apparatus was often confused with the fusion of the tactile impulses. With practice, however, this difficulty disappeared. One should be able to make consistent readings in a week by practising with the apparatus for a couple of hours each day. Difficult as it was to get consistent results at first, the final readings obtained when one had become accustomed to the use of the apparatus were so accurate that separate measurements of the critical frequency of percussion for the same pressure often varied by not more than 1 per cent.

At the beginning of this work the results were rather confusing, irregular, and discouraging. At times the readings would agree very well, and at other times, for no apparent reason, a very much smaller reading would be obtained for the same pressure of the air. It was finally decided to take a great number of readings and plot them individually on the graph paper. Much to our surprise it was found that the points arranged themselves along two curves, one much lower than the other. It was now quite apparent that there were two points of fusion of interrupted stimuli. This was verified by starting the rotation of the disk very slowly at some pressure of the air until one fusion point was reached. The speed was then increased and the sensation again became interrupted. On further increasing the speed a second point was reached where there was apparent fusion of the stimuli. This second fusion point is not of the same nature as the first; it was less satisfying, so to speak, but still it was a definitely measurable point of fusion. In making readings, therefore, care was taken to observe and record which fusion point was under observation. Consequently the problem resolved itself into the investigation of the relation between the critical

Table I.—Normal Curves. First Fusion Point.

Pressure.	Log P.	D Dry.	D Water.	D Vaseline.	D Vaseline.
Cm. of Mercury.		Hollenberg.			Allen.
		Sec.	Sec.	Sec.	Sec.
1·0	0	0·01020	0·00980	0·00890	0·01070
1·2	0·079	0·00951	0·00902	0·00822	. .
1·4	0·146	0·00889	0·00840	0·00763	0·00886
1·6	0·204	0·00833	0·00795	0·00711	
1·8	0·255	0·00786	0·00745	0·00674	0·00769
2·0	0·301	0·00748	0·00706	0·00628	. .
2·2	0·342	. .	0·00670	0·00595	0·00685
2·4	0·380	0·00674	0·00632	0·00567	. .
2·6	0·415	. .	0·00606	0·00530	0·00605
2·8	0·447	0·00620	0·00569	0·00507	. .
3·0	0·477	0·00588	0·00545	0·00475	. .
3·2	0·505	. .	0·00510	0·00448	. .
3·4	0·532	0·00535	0·00492	0·00427	0·00480
3·6	0·556	. .	0·00470	0·00411	. .
3·8	0·580	. .	0·00440	0·00390	0·00432
4·0	0·602	. .	0·00420	0·00373	. .
4·2	0·623	. .	0·00400	0·00353	0·00392
4·4	0·644	. .	0·00390	0·00330	. .
4·6	0·663	. .	0·00350	0·00300	. .
4·8	0·681	. .	0·00315	0·00270	0·00293
5·0	0·699	. .	0·00258	0·00240	0·00243

frequency of percussion and the air pressure at the first fusion point and at the second.

The significance of these two fusion points we do not at present

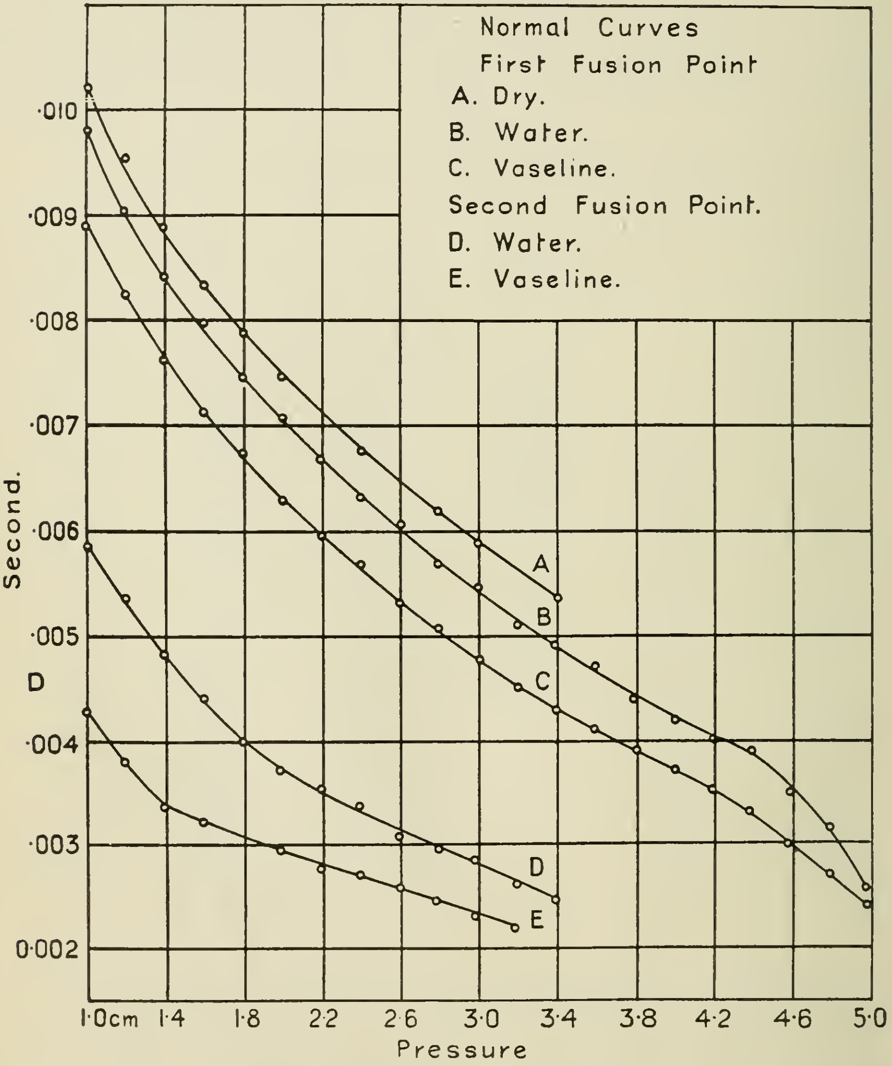

Fig. 1.—Normal tactile persistency curves.

understand. The first quite probably represents a superficial, and the second a deep tactile, sensation.

The normal curves were obtained in the manner already described, and the measurements are given in Table I. The corresponding curves are plotted in fig. 1. In the first investigation of the first fusion point the ordinary dry finger was used. Readings were obtained with difficulty, especially at the higher pressures, because of the drying effect of the air pulses upon the skin, which quickly became dry and hard, and therefore less sensitive. This is shown in the figure by its position relative to the other normal curves. Since the drying effect was disconcerting, it was decided to use water with which to moisten the finger before each reading. Very consistent results were easily obtained, but there was still a defect in that the finger would get cold on account of the rapid evaporation of the water. It was finally decided to use a thin film of vaseline as a covering for the finger-tip. It served ideally for the purpose. It did not evaporate, and consequently the temperature remained constant. The finger-tip was always kept soft and impressionable. It will be seen from the curves in fig. 1 that the vaseline normal is the lowest of the three for the first fusion point, and therefore the skin is most sensitive when it is applied. The water curve is above the normal for vaseline, which we believe is solely due to the temperature effect of the evaporation of the water. We know from experiment, although we have not taken a complete curve, that when the finger is cold it is less sensitive, and therefore relatively high readings are obtained.

TABLE II.—NORMAL, FATIGUE, AND REFLEX CURVES. SECOND FUSION POINT.

Pressure.	Log P.	D Normal.	D Normal.	D Fatigue.	D Reflex.
Cm. of Mercury.		Water. Sec.	Vaseline. Sec.	Vaseline. Sec.	Vaseline. Sec.
1·0	0	0·00585	0·00425	0·00751	0·00336
1·2	0·079	0·00535	0·00379	0·00662	0·00305
1·4	0·146	0·00480	0·00335	0·00585	0·00285
1·6	0·204	0·00438	0·00320	0·00495	0·00274
1·8	0·255	0·00396	0·00305	0·00437	0·00264
2·0	0·301	0·00370	0·00295	0·00381	0·00260
2·2	0·342	0·00352	0·00275	0·00353	0·00249
2·4	0·380	0·00335	0·00270	0·00320	0·00245
2·6	0·415	0·00305	0·00259	0·00297	0·00235
2·8	0·447	0·00295	0·00245	0·00270	0·00228
3·0	0·477	0·00285	0·00232	. .	. .
3·2	0·505	0·00261	0·00220	. .	. .
3·4	0·532	0·00245	. .	. .	. .

The second fusion point was investigated in a similar manner, and two normal curves were obtained, one with water, the other with vaseline. The measurements for these are given in Table II., and the curves are also shown in fig. 1. They maintain the same relative position as the corresponding curves for the first fusion point, indicating that the finger is more sensitive when vaseline is applied and thus no cooling effect produced. From the figure their position relative to the curves for the first fusion point may also readily be seen.

The laboratory in which the experiments were conducted was always comfortably warm, sometimes uncomfortably so. Since the sensitiveness of the skin decreases with decrease of temperature, it is evident that there is an optimum temperature for the tactile sensation as for all vital processes.

As the fig. 1 shows, the normal curves connecting the duration of the impression at the critical frequency of percussion, D, and the air pressure, P, are not straight lines. The regular curvature, however, suggested that some linear relation existed between these two quantities. By plotting logarithms of the pressure, and the time intervals obtained at the critical frequency, Table I., the graphs are shown in fig. 2 to be straight lines with an abrupt change of slope at the pressure of 4·4 cm. for the first fusion point, and at the much lower pressures of 1·4 cm. (vaseline curve) and 1·8 cm. (water curve) for the second.

It is also to be noticed that the change of slope of the lower portions of the curves for the second fusion point is in the opposite direction to that of the curves for the first. This shows that increase of pressure has much less proportionate effect upon the deep tactile sensation than upon the superficial. Further, the opposite changes of slope will obviously cause intersection of the curves for the two fusion points, which indicates that at a pressure somewhat higher than our greatest experimental value the superficial and deep tactile sensations become indistinguishable from each other and merge together forming a single tactile sensation.

With one exception the curves described in this communication were obtained by HOLLENBERG. In fig. 6, however, there is shown a normal (vaseline) curve obtained by ALLEN, the data for which are given in Table I. This lies much above the corresponding normal (vaseline) obtained by HOLLENBERG, the two, however, converging and ultimately meeting. The change of slope occurs at the same pressure in each of the two curves. As far as generalisation from two cases is permissible, it appears that normal tactile sensations differ with individuals in sensitiveness. No doubt the customary manual occupations have their influence. The disparity in age, one being double the other, between the authors may likewise account for the difference. It also suggests that study of many individuals may bring to light phenomena of touch analogous to anomalous vision and colour blindness in sight. It is especially to be noted, that though only one curve obtained by ALLEN is given here, yet sufficient measurements under fatigued and various enhanced conditions of the tactile sensation were obtained by him to verify and confirm the more extended measurements of HOLLENBERG.

The normal curves all conform to the equation

$$D = -K \log P + C,$$

where D is the time interval at the critical frequency of percussion, P the pressure of the air, and K and C are constants depending upon the nature of the physiological processes involved and the experimental method of investigation. It is the constants that vary from curve to curve, and in the two parts of the individual curves. The negative sign indicates that the duration of impressions at the critical frequency of percussion decreases in direct proportion to the increase of the logarithm of the air pressure.

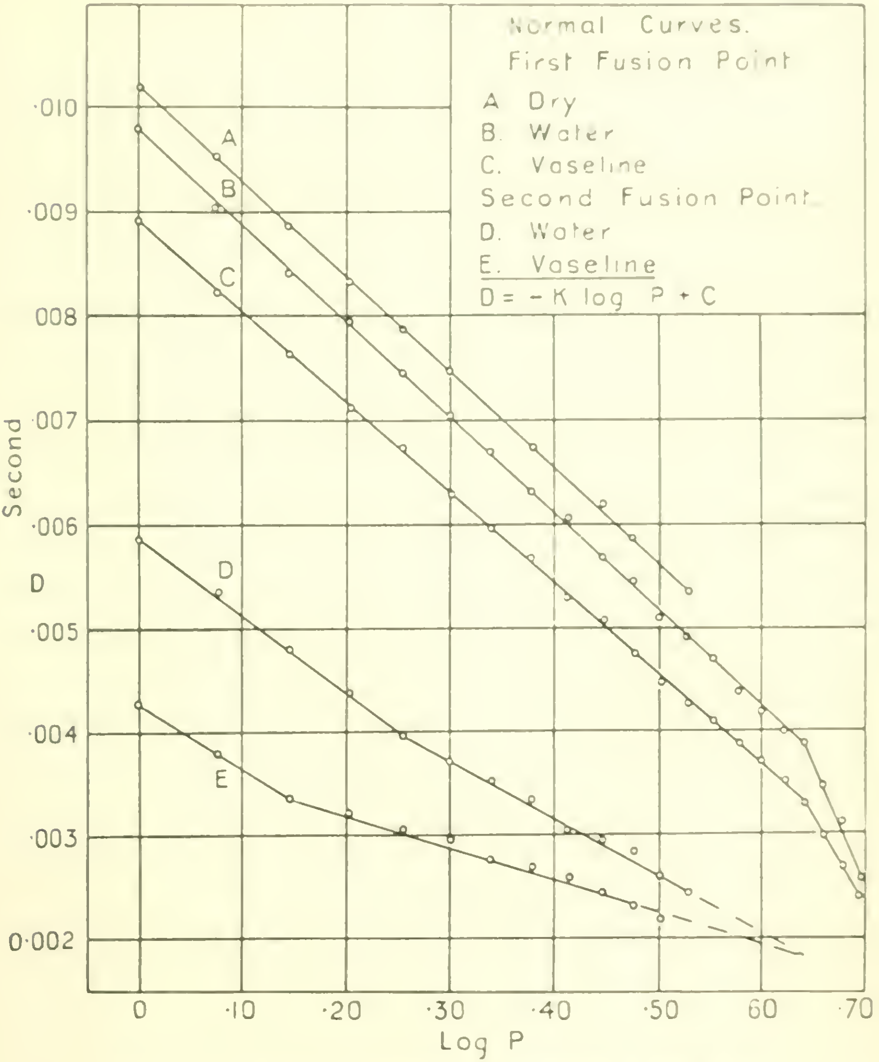

FIG. 2.—Normal tactile persistency curves reduced to linear form.

For the normal (vaseline) curve of Hollenberg, fig. 2, curve C, the equations with numerical values of the constants, K and C, for the upper and lower branches of the curve respectively, are:

$$D = -{\cdot}00833 \log P + {\cdot}0089$$
$$D = -{\cdot}0158 \ \log P + {\cdot}0135.$$

In vision, when the logarithms of the intensity of illumination, I, are plotted against the reciprocals of the duration of the sensation at the critical frequency of flicker, D, we obtain a similar equation:

$$\frac{1}{D} = K \log I + C,$$

which is known as the Ferry-Porter law. This law applies to white light as well as to colours. One of the curves obtained by one of the authors in an investigation[1] on colour vision is here reproduced in the lower part of fig. 3. This also shows an abrupt change of slope at a certain low value of the illumination. It will be noticed that the slope of this curve is in the positive direction instead of the negative as in the tactile sensation.

Much to our surprise, on reviewing the paper by Weinberg and Allen, "On the Critical Frequency of Pulsation of Tones," referred to above, we found that the curve obtained by plotting the logarithms of the intensity, P, of the tone, against the critical frequency of pulsation, D, consisted of two similar straight lines with a change of slope, which conform to the equation:

$$D = K \log P + C.$$

This curve is given in the upper part of fig. 3. It may be noted here that in the original paper this characteristic feature of the curve was not detected, and a different equation involving the square root of log P was erroneously given. This, however, was corrected in a later communication[2] to the same journal. In the three equations to the curves for measurements on the different senses, the numerical values of the constants, K and C, are of course not the same.

Thus for the three senses so far investigated by the method of intermittent stimulation, we find a direct logarithmic relation between the intensity of stimulation and the time interval of the stimulus when at the critical point of fusion. This uniformity in the response of the three types of sensory end-organs to intermittent stimulation is indeed a remarkable phenomenon, but it is to be expected when we realise that embryologically the retina, the auditory receptors, and the peripheral nerves with their sensory end-organs are all developed from the same source, the neural epithelium of the ectoderm.

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[1] Allen, "The persistence of vision of colours of varying intensity," Phil. Mag., 1919, xxxviii. 87.

[2] Phil. Mag., 1924, xlvii. 941.

The change of slope of the curves in the three sensations, light, sound, and touch, shows that at some definite intensity of stimulation there is a definite change in the sensitiveness of the receptors. There are two possible explanations of this: first, that the change is in the receptor organs proper, and indicates that at a definite intensity of stimulation their sensitiveness becomes greater or less; second, that when this critical intensity is exceeded the nerve impulses have either a freer or a more hindered passage through the synaptic resistances of the reflex arc. This change of slope evidently represents a general

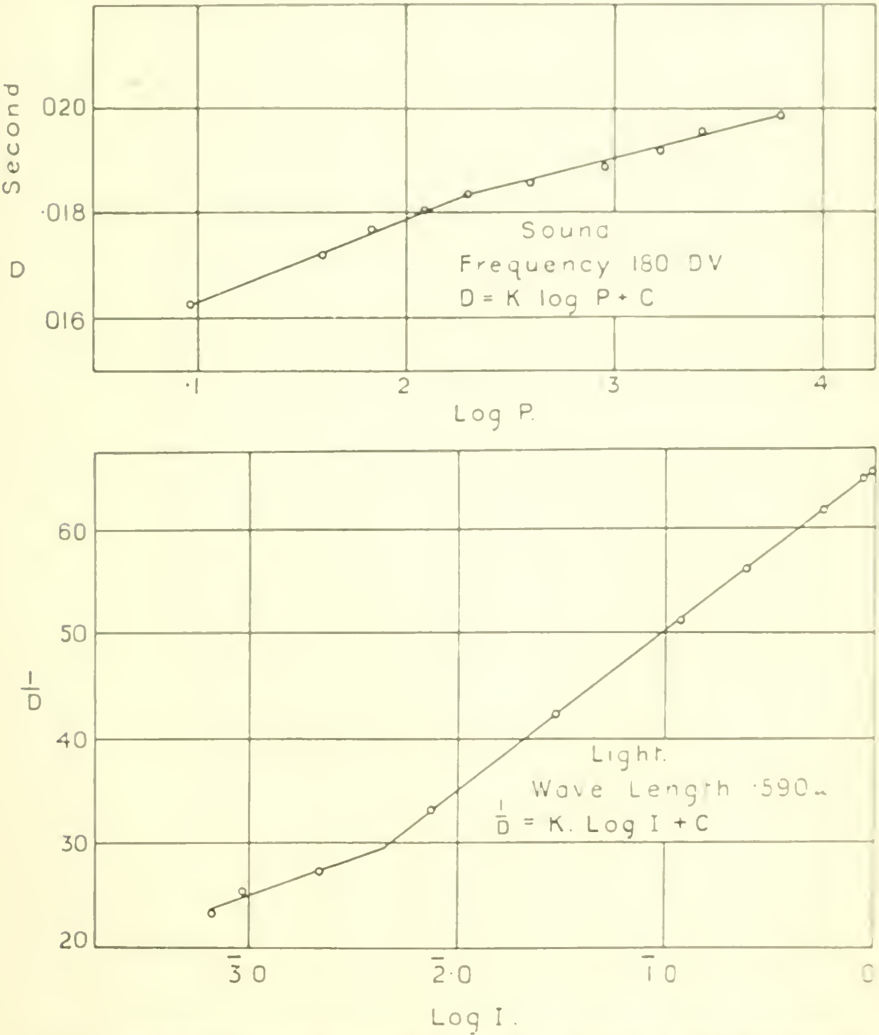

Fig. 3.—Curves showing difference in responsiveness to weak and strong stimulation by sound (upper) and light (lower).

property of the sensory nervous system, and in all cases is either an end-organ effect or a central synaptic effect. In the case of the eye the change in direction of the curve has always been attributed to a change from rod, or scotopic, vision to cone, or photopic, vision. For this reason it has been used in support of the "duplicity theory" of vision of von Kries.[1] In view of the occurrence of this peculiarity in the analogous curves for the other sense organs besides the eye, the effect probably cannot be ascribed to the two kinds of receptors. It seems clear, therefore, that the phenomenon does not support the duplicity theory of von Kries. But a general and more fundamental duplicity theory may now be formulated in the light of these curves for the sensory systems so far studied, that in each sensory system there is some critical intensity of stimulation at which the rate of response to interrupted stimuli, or the sensitiveness, suddenly increases or decreases.

Since we have just considered the curves for light, sound, and touch, it is interesting to compare the relative responsiveness of these three sensoria, as measured by the critical frequency method, at the intensities of stimulation to which they are usually subjected. It is found that the tactile sensation is most responsive, then hearing, and finally sight. For example, in moving pictures in order that a continuous sensation may be obtained the pictures must appear in succession at the rate of about 20 per second. If we were to have an analogous device for producing a continuous sensation of touch, the rate of separate impulses would have to be about 50 per second for the lowest, and 200 for the highest pressure employed in this investigation.

These conclusions are in agreement with Starling.[2] "The tactile apparatus is smarter in its response than any other of the sense organs. On this account stimuli are still perceived as discrete, when they are repeated at a rhythm which would result in complete fusion in the case of any of the other sense organs. . . . The sensations evoked by placing the finger against the edge of a cog-wheel do not become continuous until the wheel is revolving at such a rate that the stimulation on the skin by the serrations occurs at a greater rate than 500 or 600 per second."

From the physical point of view the order of responsiveness of these three sensations seems paradoxical. But if the dynamical equivalents of the liminal stimuli of the sensations be accepted as the criteria of relative sensitiveness, it is evident that the order will be reversed, the eye being the most sensitive, then the ear, and finally the tactile sense. Roughly, the responsiveness to intermittent stimuli varies inversely as the sensitiveness.

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[1] Parsons, "Colour Vision," p. 208.

[2] *Op. cit.*, p. 630. Also Sherrington, *op. cit.*, p. 924.

TACTILE FATIGUE.

The effect of fatigue upon the tactile sensation was now studied. The part of the index finger, the volar face of the terminal phalanx,

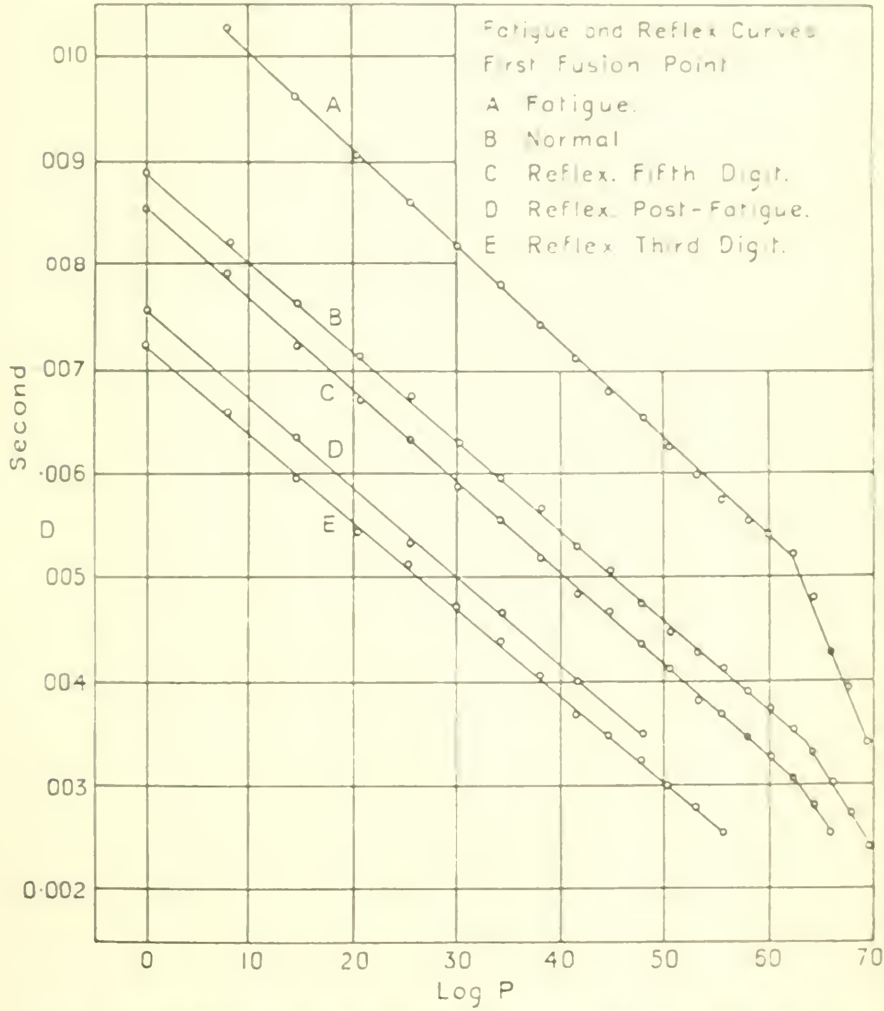

FIG. 4.—Curves showing fatigue and enhancement of the superficial tactile sensation.

upon which all measurements were made in these investigations, was rubbed upon a piece of paper smeared with vaseline, with fair pressure exerted by the arm, for about four minutes before each reading of the critical frequency of percussion was made. Fatigue curves were obtained for the first and second fusion points which are shown as curves, A, in figs. 4 and 5, the data for which are given in the columns marked " Fatigue " in Tables III. and II. respectively. By comparing these curves with the normals, B, in each figure, it will be seen how pronounced is the effect of fatigue of the receptor end-organs upon the critical frequency of percussion for each fusion point. The change of slope of the fatigue curve for the first fusion point, fig. 4, occurs at nearly the same pressure as the normal value. It is obvious also that the normal and fatigue curves converge and would intersect at a pressure above our experimental values for which D would measure about 0·001 second.

TABLE III.—FATIGUE AND REFLEX CURVES. FIRST FUSION POINT.

Pressure.	Log. P.	D Normal.	D Fatigue.	D Reflex.	D Reflex.	D Reflex.	D Reflex.	D Reflex.
Cm. of Mercury.		Vaseline. Sec.	Sec.	3rd Digit. Sec.	5th Digit. Sec.	Post-Fatigue. Sec.	Light Touch. Sec.	4th Digit. Sec.
1·0	0	0·00890	. .	0·00724	0·00855	0·00756	0·00820	. .
1·2	0·079	0·00822	0·01026	0·00660	0·00792	. .	. .	. .
1·4	0·146	0·00763	0·00960	0·00596	0·00722	0·00635	0·00707	. .
1·6	0·204	0·00711	0·00905	0·00545	0·00670	. .	0·00652	. .
1·8	0·255	0·00674	0·00860	0·00511	0·00630	0·00533	. .	. .
2·0	0·301	0·00628	0·00817	0·00472	0·00587	. .	0·00580	0·00471
2·2	0·342	0·00595	0·00780	0·00440	0·00555	0·00465	. .	. .
2·4	0·380	0·00567	0·00742	0·00405	0·00519	. .	0·00519	0·00417
2·6	0·415	0·00530	0·00710	0·00367	0·00485	0·00400	. .	. .
2·8	0·447	0·00507	0·00680	0·00349	0·00466	. .	0·00465	. .
3·0	0·477	0·00475	0·00655	0·00325	0·00438	0·00349	. .	. .
3·2	0·505	0·00448	0·00626	0·00299	0·00412	. .	0·00420	0·00309
3·4	0·532	0·00427	0·00599	0·00278	0·00380	. .	. .	. .
3·6	0·556	0·00411	0·00575	0·00252	0·00366	. .	0·00375	. .
3·8	0·580	0·00390	0·00555	. .	0·00345	. .	. .	0·00255
4·0	0·602	0·00373	0·00544	. .	0·00325	. .	0·00339	. .
4·2	0·623	0·00353	0·00523	. .	0·00305	. .	. .	. .
4·4	0·644	0·00330	0·00480	. .	0·00281	. .	0·00322	. .
4·6	0·663	0·00300	0·00429	. .	0·00252	. .	0·00300	. .
4·8	0·681	0·00270	0·00395	. .	. .	. .	0·00275	. .
5·0	0·699	0·00240	0·00340	. .	. .	. .	0·00244	. .

In the case of the second fusion point, fig. 5, the change of slope of the fatigue curve occurs at a higher pressure than normal, the precise values being 1·9 cm. and 1·4 cm. respectively. This displacement of the break in continuity may possibly be adduced as evidence that the change in physiological sensitiveness is in the end-organ proper and not in the synaptic resistance of the arc.

The effect of fatigue upon the sensations of light and sound were experimentally determined and discussed in the papers to which reference has been made above. In these two senses also the fatigue curves lie above the normal as in the tactile sensation.

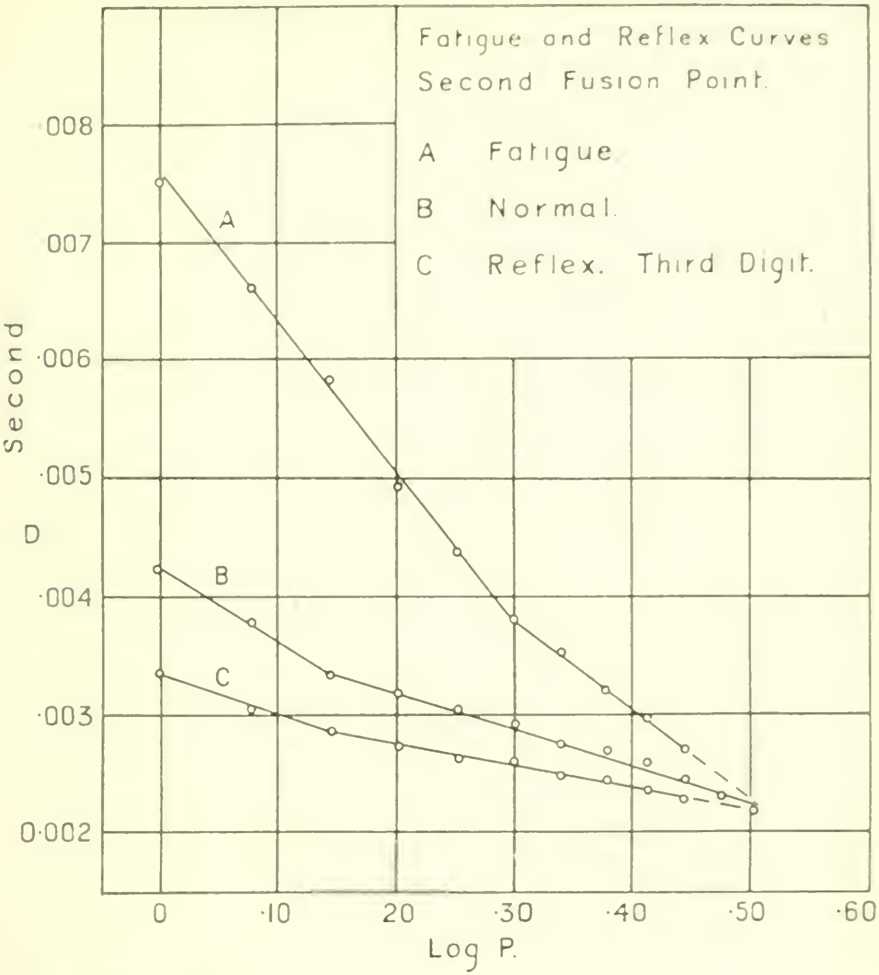

FIG. 5.—Curves showing fatigue and enhancement of the deep tactile sensation.

TACTILE ENHANCEMENT.

The problem that next presented itself for solution was the production and measurement of the reflex enhancement of the tactile sensation, as had been done by ALLEN in the sensation of light. The most obvious manner of accomplishing this was by fatiguing the tactile sensation in an adjacent finger and observing the effect on the index finger, in analogy with ALLEN'S method of fatiguing one retina with a colour and observing the enhancement of the colour sensations in the other. Accordingly, the observer tied a rather tight elastic bandage around the third digit of the right hand, placed a little vaseline on the index finger, and proceeded to take readings as usual. At first one was conscious of the presence of the bandage, but soon it was forgotten. Before the first reading was made the bandage was allowed to be on the finger for twenty minutes, and it then remained in place during the time required to obtain the complete reflex curve. The measurements for the first fusion point are in Table III. and for the second in Table II., and the corresponding curves are shown in figs. 4, E, and 5, C, respectively. The reflex effect on the sensitiveness of the index finger was remarkable, both in the first and second fusion points. The position of the reflex curves below the normal clearly indicates that the opposite effect of fatigue was produced, and that the tactile receptors in the index finger are greatly enhanced in sensitiveness. The curves again are straight lines when plotted with logarithms of the pressure.

No change in slope could be obtained in the reflex enhancement curve, E, fig. 4, for the first fusion point, because with our apparatus we could not measure any time intervals less than 0·002 second, which would be required if the break in continuity is to be obtained. This could easily be accomplished of course by constructing a disk with a larger number of openings. In the enhancement curve, C, fig. 5, for the second fusion point, the change of slope occurs exactly at the same pressure as in the normal.

Thus by stimulating one region of the skin, an adjacent portion becomes more sensitive. The principle of reflex enhancement of sensitivity of receptors seemed to be proved. But there were certain objections which led us to make further inquiry. These were, first, that tying up one finger would have a psychological effect by compelling better attention ; second, that the innervation of the second and third digits is identical. The first objection really has no weight, because after a few minutes one becomes oblivious of the bandaged finger, and there is no reminder to induce better attention. The second objection also becomes of little value, because the fibres that supply the third are separate from those that supply the index finger, and any effect observed in the latter must be due to central action brought about by the fatigue of the former digit. However, in order to demonstrate conclusively that the enhancement passed from receptors supplied by one nerve to receptors supplied by another, the fifth digit was treated in a similar manner to the third by wrapping it tightly with a piece of Esmarch bandage. Fifteen minutes after this was applied, the readings were begun with the index finger, and, as expected, enhancement was found to result. The data for this curve, as well as for all fatigue and enhancement curves for the first fusion point, are given in Table III. The curve, C, fig. 4, shows undoubted enhancement, though not to so great an extent as in the case of fatigue of the third digit. This effect was measured only for the first fusion point. Thus fatigue of the ulnar nerve causes enhancement of the receptors of the median nerve, for the volar aspect of the ungual phalanx of the index finger is supplied by the latter nerve. Since the reflex enhancement of the tactile sensation from the fatigued or stimulated fifth digit was smaller than from the third, the measurements could be extended to higher pressures. The curve, C, therefore shows the characteristic change of slope, which occurs also at the same pressure as in the normal curve.

A few measurements were also made of the enhancement due to stimulation of the fourth digit in the same manner as before. The few readings are given in Table III., but they are not plotted in the figures. They indicate, however, that the enhancement curve is slightly above that for the third digit, E, fig. 4. No doubt the more complex innervation of the fourth digit compensates for its greater distance from the index finger than the third.

POST-FATIGUE AND LIGHT-TOUCH ENHANCEMENT

During the study of the effects of fatigue, it was found that a remarkable enhancement of the tactile receptors of the index finger was produced by waiting a few minutes after fatiguing it before the critical frequency measurements were made. This form of enhancement of the sensitiveness of the skin we have termed post-fatigue enhancement. A partial curve, D, fig. 4, was obtained under such conditions, and it can readily be seen that the amount of enhancement is large and significant. The data are in Table III. This post-fatigue enhancement greatly elucidates the nature of the underlying tactile processes. As is the case in vision, the fatiguing afferent stimuli bring about reflex enhancement of the sensitiveness of the receptor end-organs. During the time of stimulation, the fatiguing effect exceeds the enhancement which proceeds *pari passu* with it, and fatigue predominates. When stimulation ceases, fatigue shortly disappears, but the enhancement continues to affect the receptors, and when the sensitiveness of the skin is measured it shows enhancement due presumably to continued reflex discharges. It would be difficult to explain these effects on any other basis, especially when we consider the evidence which the next experiment adds to the argument.

Working on the hypothesis that the afferent stimulus causes an efferent or reflex discharge which enhances the receptors, and, further, that the state of receptivity or sensitiveness of any receptor is the algebraic sum of fatigue and reflex enhancement, readings were made after the same area of the index finger, constantly used for this purpose, had been very slightly stimulated or fatigued by gently rubbing it on vaselined paper. The object of this procedure was to transmit to the central nervous system liminal or extremely low afferent stimuli. The curve so obtained is shown in C, fig. 6, in comparison with the same normal curve, B, used with all the fatigue and reflex curves for the first fusion point. This indicates definite enhancement to be present. The same effect was also observed when the index finger was gently stimulated by light touches with the edge of a piece of paper which produced a tickling sensation. Evidently the liminal or smallest appreciable afferent

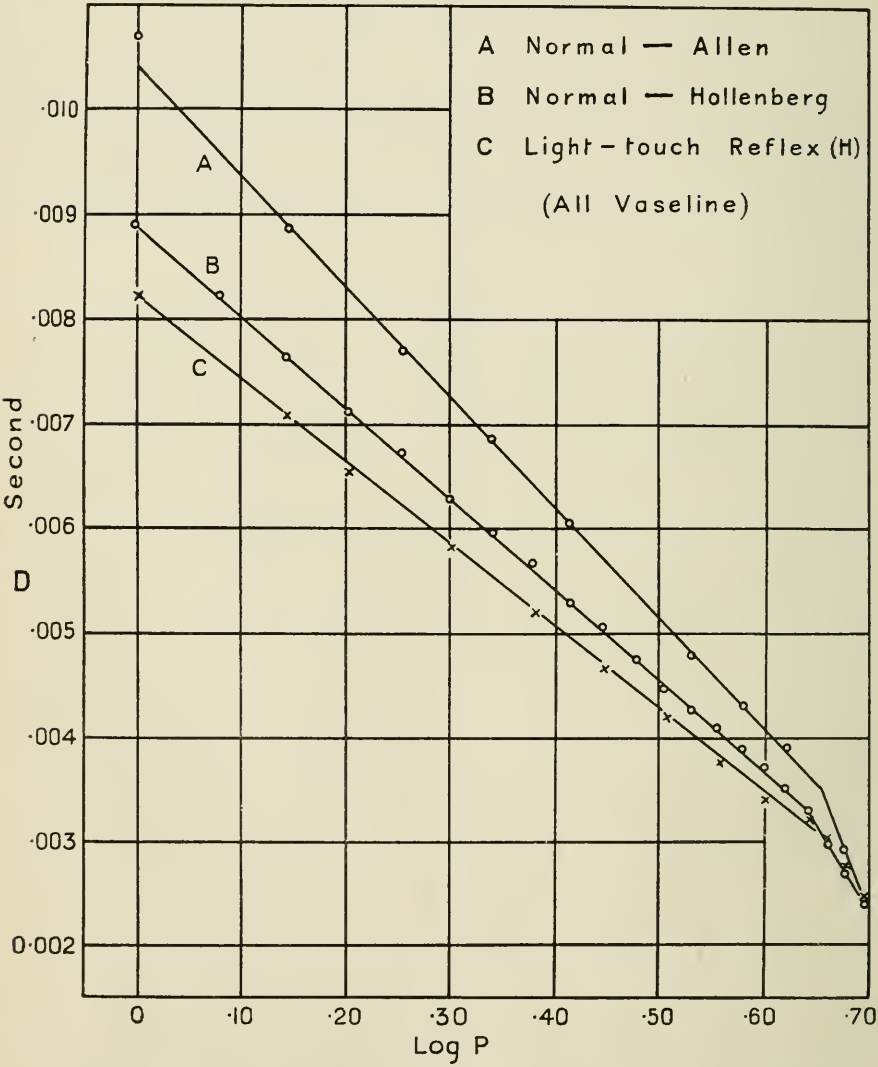

FIG. 6.—A and B, normal tactile persistency curves of the authors. C, curve showing light-touch enhancement.

impulse can evoke an efferent response which enhances the receptors to a far greater extent than the direct stimulus fatigues them. This effect we have designated light-touch enhancement.

CONVERGENCE OF THE CURVES.

On examining the curves in figs. 2, 4, 5, and 6, one cannot fail to notice that the curves for each of the fusion points are strongly convergent in their lower branches and in some cases in the upper as well. Even the normal curves of the authors in fig. 6, while far apart at first, converge and intersect at the pressure stimulus of 5·0 cm. The same phenomenon also occurs with the normal curves, fig. 2, obtained with water and vaseline, for both fusion points, though the point of intersection is not the same. Since the normal, fatigue, and enhancement curves for both fusion points, figs. 5 and 6, converge and meet, we may infer that at the pressure of intersection, fatigue and enhancement cease to be differentiated or to be distinguishable from the normal condition of the tactile sensation. Part of this may be due to the fact that to an increasing extent fatigue accompanies the act of measurement as the pressure increases. Whatever may be the explanation, the occurrence of equilibrium pressures at which fatigue and reflex effects balance each other, is strikingly analogous to the occurrence in vision of six equilibrium colours [1] in the spectrum, which produced neither fatigue nor enhancement of the colour sensations. As there are three visual sensations, the larger number of equilibrium colours is due to the numerous visual interactions. In touch there appear to be two tactile sensations and two equilibrium pressures.

TACTILE CONTRAST AND AFTER-IMAGES.

It was often observed when readings of the critical frequency of percussion were being made, that when the sensations aroused by the intermittent air pressure appeared continuous on the area of the finger studied, they were instantly perceived as intermittent on a fresh adjacent area when the finger was quickly moved. This, no doubt, is due to slight fatigue of the first area and simultaneous enhancement of the second. It is perfectly analogous to enhanced colour and light effects found in the retina on areas adjacent to the one fatigued, which are described in the paper on colour contrast referred to above. This effect was used to explain the modification of colours and light by simultaneous contrast. It seems quite probable that phenomena analogous to contrast, both simultaneous and successive, are to be found in the tactile as well as in the other cutaneous sensations. For example, gently rubbing the finger simultaneously over two contiguous areas of different degrees of smoothness would probably cause each to modify the tactile perception of the other. Two unequally heated or cooled areas also might tend to intensify each other. Successive contrast might be found to occur by touching a smooth surface after a rough, or the reverse.

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[1] ALLEN, "On reflex visual sensations," *op. cit.*

In the case of vision it was formerly suggested by Allen that positive after-images were probably due to the persistence of afferent stimulation, and negative after-images to efferent discharges. It seems probable, therefore, that similar phenomena should characterise all sensory receptors. In touch, the existence of the curves obtained by the persistence of the tactile sensations is itself proof of the presence of positive after-images. Negative after-images are not so easy to identify, and we are unable at present to designate any phenomenon undoubtedly illustrative of that efferent effect. It appears probable that they will be found associated particularly with post-fatigue and light-touch enhancement. We may, however, cite as an example of one or other of these effects the persistence of the sensation which results from pressing a cold coin against the forehead. The following quotation from Sherrington[1] seems also to be in harmony with the suggestion: "This difference between nerve and end-organ does not, however, hold if the stimulus to the latter is but little above liminal,—then the touch is felt for a moment after contact, and speedily subsides. It may be again felt for a moment at the sudden discontinuance of this stimulus; in this the reaction resembles many reflexes obtainable from the spinal cord, where discontinuance of a prolonged stimulation evokes a renewal or an increase of a reflex reply that had ceased or become feeble. 'Touches' evoked by brief stimuli, even of very slight intensity, especially from the region of the nose, may persist for very long, or leave a very protracted after-sensation. The prolongation of the sensation is of an itching, tickling quality, and may continue even for minutes. This secondary sensation may be due to a local vascular reflex initiated by the stimuli, for the itching spot can generally be seen to be flushed." It is possible that the "secondary sensation" of the peculiar quality described may be the negative tactile after-image.

The well-developed phenomena of adaptation in the sense of touch are also quite analogous to similar phenomena in vision.

It is quite probable that all sense organs possess the same general fundamental properties characteristic of direct and reflex sensory action, such as positive and negative after-images, simultaneous and successive contrast, complementary sensations, and adaptation. But the extent to which each is developed in a sense organ depends on the nature of the organ and the purpose for which it is adapted. The phenomena characteristic of binocular vision have their analogies in other sensory systems. As we have shown, one finger affects another tactually, precisely as one eye affects the other visually. Binocular visual enhancement, which is the cause of contrast, is paralleled by bidigital tactile enhancement, which probably also produces what may be termed bidigital contrast. Even the Cyclopean eye has its equivalent in the other senses, and particularly in the tactile sensation. For when the fingers touch an object, the impression is not five-fold but unitary, and its position is not referred to any one finger. Probably also phenomena analogous to colour blindness and anomalous colour vision are likewise to be found in all sensoria.

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[1] Schafer's "Text-book of Physiology," 1900, ii. 925. This also refers to adaptation.

WEBER'S LAW.

The existence of the reflex enhancement of the sensitiveness of receptors, which always accompanies the direct or fatiguing action of a stimulus, fundamentally alters the interpretation of Weber's law. Following PARSONS,[1] the law may be stated thus: "The just appreciable increase of stimulus bears a constant ratio to the original stimulus."

"Stated algebraically, if E is the measure of a sensation and δE the just appreciable difference, S the measure of the stimulus and δS a small increment, then

$$\delta E = \frac{C \cdot \delta S}{S} \text{ (Weber's law).}$$

where C is a constant; therefore on the questionable assumption that it is permissible to integrate small *finite* quantities,

$$\begin{aligned} E &= C\int\frac{\delta S}{S} \\ &= C \log S + C'' \text{ (Fechner's law),} \end{aligned}$$

where C″ is another constant."

Thus Fechner's law states that the sensation varies as the logarithm of the stimulus.

The law to which the experimental data in the preceding figures conform, $D = -K \log P + C$, is also true in light and sound. Obviously it is analogous to the expression for Fechner's law, from which, indeed, as applied to vision, it has been derived by PEDDIE.[2]

The accuracy with which the measurements of the critical frequency of percussion fit the curves, as well as similar measurements in light and sound, clearly proves that between the limits of stimulation employed, Fechner's law is correct, as is also the more fundamental law of Weber upon which it ultimately rests.

But Weber's law has been believed to refer only to the direct action of a stimulus, since there was no knowledge of a concomitant enhancing sensory reflex. The opposing physiological actions concerned were, however, always operative in the experiments by which the law was tested. The law, therefore, is not fundamental in regard to the two physiological actions involved, but represents the difference between them. Weber's law would probably be entirely different if experiments were made upon sensory receptors from which the reflex enhancement of sensibility were entirely eliminated, leaving the result of the direct action alone to be perceived.

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[1] "Colour Vision," p. 19. For another method of deriving Fechner's law see MYERS, "Text-book of Experimental Psychology," 1922, part i, p. 248.

[2] PARSONS, "Colour Vision," p. 162.

We may, therefore, represent Weber's law thus :—

$$\frac{\delta S}{S} = \pm f(A) \mp f'(E),$$

where the two right-hand members of the equation respectively represent unknown functions of the direct afferent and reflex efferent actions of the stimulus on the receptor organs. It is always the algebraic sum of these two effects that is perceived.

The situation in regard to the law in question is much the same as would be the case were a mathematical law of action to be deduced from measurements on the attraction of two magnetic poles if, at the same time, an electrostatic repulsion were operating between them of which the experimenter was unaware. A law might be formulated, but it would represent the difference between the two opposing forces.

From the standpoint of physiology, Weber's Law is in a similar position. In reality it is not a primary law of action at all, but represents the difference between the two fundamental sensory processes, each of which no doubt can be mathematically formulated.

But the exact forms of both functions indicated in the above equation are unknown. All that we know is that their difference integrates into a logarithmic function. If either of the unknown functions is experimentally determined, the other can then be deduced from the equation. Possibly this might be accomplished by using a drug which would prevent the efferent nerves from functioning, without interfering with the afferent. Or the efferent impulses might be inhibited by employing antagonistic sensory reflexes from some appropriate source. The direct effect of the stimulus upon the unenhanced receptors might then be separately determined.

From this standpoint it is not to be wondered at that Weber's law does not hold for extreme intensities of stimulation, both high and low. In the case of light and colours falling upon the retina, there is during the first hundredth or fiftieth of a second an " overshooting " of the sensation, which causes blue light to be perceived with five times, and red light with twice, its normal intensity. This is most probably due to the initial development of the enhancement of the visual receptors by the sensory reflex. During the time of adjustment of the two physiological actions in light perception, and in all sense organs, the normal ratio of afferent to efferent effects would probably be greatly disturbed. We have seen from experiment that, in the case of light-touch, enhancement of sensitiveness greatly predominates over fatigue, a phenomenon that may also exist in the other sensory receptors, though no experimental proof of this occurs to the writers. It cannot be expected therefore that Weber's law formulated for medium values of stimulation will also apply to values so small as to cause enhancement to predominate over fatigue. The full knowledge of the behaviour of both physiological processes, however, will doubtless bring both high and low intensities under one comprehensive law of action.

SENSORY TONE.

Dr ALEXANDER GIBSON, F.R.C.S., has directed our attention to the significant fact that the state of equilibrium maintained between the fatiguing and enhancing actions in the tactile sensorium is analogous to tonus in muscular tissues. In the latter the tone serves the purpose of giving efficient and prompt contraction of the muscle when an external stimulus is applied. So in the tactile sensation the receptors may be spoken of as being in "sensory" tone between the direct and reflex influences which are striving to maintain a condition of great sensitiveness and readiness to permit instant perception. This, no doubt, is true of all the sense organs. The principle is particularly exemplified in visual and auditory perception, where the receptors are able to function for long periods of time without fatigue.

FLUCTUATION.

In recent investigations by WATERSTON [1] it was found that a marked fluctuation occurred in the number of cold and heat spots in any one area of the skin. In considering his experiments he concludes: "The spots are readily exhausted by a repetition of the stimulus. This is an important phenomenon, but of greater importance is the observation we have made, that dulling of one spot is accompanied by the awakening to thermal sensibility of an adjacent spot. If the point of a fine metal probe cooled to the requisite degree is brought into contact with a cold spot, and the touch repeated again and again at intervals of about a second, at first the contact produced a clear and distinct sensation of cold. After a few contacts, however, the sensation of cold is no longer excited by the stimulus, but that of touch only. The cold sensation may disappear after two or three contacts, or only after some eleven or twelve, and it may disappear and then reappear once or twice, and then disappear.

"If now the stimulus point be moved slightly to one or other side, the sensation of cold is at once set up from a spot from which before no such sensation was elicited.

"The explanation of this varying activity of the spots constituted a puzzling difficulty until we came to realise that we were dealing with a general character of the physiological activity of organs, namely, that under ordinary conditions the whole of an organ is not in a state of activity, but a small part of it only ; that there is a coming and going of activity among the different parts—change from activity to quiescence. This feature we have termed "fluctuation," and recognition of its occurrence affords an explanation of many otherwise extremely puzzling phenomena.

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[1] "The sensory activities of the skin for touch and temperature," Brain, 1923, xlvi. 200.

"The sensation of itching or tickling shows the same peculiarity. If the surface of the skin on the hairless part, for example, on the front of the wrist, is gently rubbed with a bristle, the sensation of tickling is elicited distinctly from some parts and not from others. If one of these sensitive areas is gently rubbed, the tickling sensation gradually disappears, but if the bristle is moved to an adjacent area, usually distal, the tickling sensation is again excited in an accentuated degree.

"This gives an explanation of why itching tends to spread by scratching, for the scratching excites the sensitive part, and its sensitiveness becomes exhausted while that of an adjacent area is in turn excited."

These observations appear to be in perfect agreement with our experimental evidence for the existence of a tactile sensory reflex, from which the existence of sensory reflexes for the other cutaneous sensations is also rendered extremely probable. WATERSTON recognises the alternation in receptivity of the sensory end-organs, and terms the end-result "fluctuation." But in the experiments which have been described in detail above, it has been shown that alternation in the sensitiveness of the tactile receptors is not a primary effect. Fluctuation is not due to fatigue alone, nor to enhancement alone ; but it is due both to fatigue and to the reciprocal reflex action of contiguous areas upon each other. This produces a pendular oscillation of fatigue and enhancement from one set of receptors to the other. When one area is stimulated the effect does not remain in that area alone, but the sensitiveness of a large surrounding region is reflexly enhanced. This is indeed a fluctuation in sensitiveness, but the fluctuation is the result of a reflex process. The sensory reflex and fluctuation stand in the relation to each other of cause and effect.

The two illustrative phenomena of itching and tickling to which WATERSTON refers may with advantage be considered more in detail.

In the former, when an area of the skin becomes irritated, relief is obtained by scratching. This is a process of fatiguing the sensorium by which the sensitiveness of the receptors that are scratched is greatly reduced, with consequent relief. But from our experiments we know that a process of fatigue in one area causes enhancement of the adjacent receptors, which are thereby rendered supersensitive, and the scratching process has to be transferred to them. The originally irritated area shortly becomes more irritated, and the scratching process must be repeated with even greater intensity. This is no doubt due partly to post-fatigue enhancement, by which an end-organ after fatigue shortly becomes more sensitive than normal, and partly to the reciprocal enhancing action from the secondary area.

It is quite evident therefore that fluctuation is not a primary action, or an "inherent property of some part of the receptors," [1] but is purely an end result produced by fatigue and its associated enhancing sensory reflex.

The second phenomenon of tickling, referred to by WATERSTON, is of a somewhat different nature. Its occurrence is no doubt due to light-touch enhancement, the existence of which has been experimentally demonstrated. Light touch enhances the sensitivity of the receptors, not only in the area stimulated, but also in the region surrounding it. When the tickling point is lightly moved, it is constantly coming in contact with enhanced receptors, causing their further enhancement by the same process. Thus, by means of a very weak stimulus, motor reflexes are evoked of a magnitude which in ordinary circumstances would require the most powerful afferent stimuli.

It would appear to follow that if the tickling point move across the skin with a speed equal to the rate at which the enhancement spreads, which is the latent period of the reflex, no tickling would be produced. This would imply a critical velocity of tickling, which experience shows exists, above which no tickling could be elicited.

Knowing the lengths of the afferent and efferent fibres to the area of the skin observed, and the rate of nerve conduction, from the measurement of the critical velocity we might evaluate the reflex time or the latent period of the tactile reflex.

The same principle of light-touch enhancement applies also to lubricated areas. The lubricator prevents immediate contact between the stimulating agent and the receptors, thus evoking the greatest enhancement with the least stimulus, and with avoidance of fatigue. This in turn may promote strong secretory and motor reflexes. This principle no doubt applies with especial force to lubricated areas, such as the mouth, conjunctivæ, and the genitalia.

Since there are rhythmical changes in the capillary blood-supply of the skin, it might be suggested that these reflex actions are in reality capillary effects. But it is known that motor and secretory reflexes are always accompanied by increased blood-supply to the reacting tissue. It is then to be expected that when the sensory end-organs become enhanced and their activity increased, their blood-supply will also be augmented by a secondary subservient vasomotor reflex.

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[1] "The law of fluctuation, etc.," P. T. HERING, Brain, 1923, xlvi. 209.

Referred Pain.

Though the experimental investigations described in this communication are limited to the tactile sensation, the fact that they are similar to fatigue and reflex phenomena in vision leads us to conclude that they are to be found in all sensory systems. We may assume with confidence, therefore, that like effects are to be found in the other cutaneous sensations, heat, cold, and pain.

In consideration of the last of these, pain, the reflex theory suggests interesting extensions to many phenomena associated with it, especially in pathological conditions. It often happens, for example, that certain areas become insensitive to touch or pain. In such cases the efferent part of the reflex arc is probably temporarily inhibited from action or blocked, which prevents enhancement of the receptors, thereby causing an unusual degree of fatigue or depression of sensibility to result and to be maintained. The opposite condition of hypersensitiveness to touch and pain also often occurs. This may be explained by changes in the central nervous system, by means of which unusually large efferent discharges are uncontrollably released which enhance the sensitiveness of receptors to an exceedingly high degree. In this condition the lightest stimulus that normally is scarcely perceived would give rise to painful sensations. In such cases fluctuation would entirely disappear, which in itself would therefore be an indication, and probably the first indication, of some abnormal condition in process of development.

It may also happen that when some region is rendered supersensitive by inflammation, strong afferent impulses proceed to the central nervous system and give rise to equally strong efferent discharges by which the receptor organs of pain and touch are greatly enhanced in sensitiveness. These enhancing impulses may travel back not only to the original receptors but to other areas more or less removed from them. Referred pain, therefore, will be felt in these regions though the latter areas are not themselves in any pathological condition. The secondary areas so enhanced may in turn give rise to referred pain in a third area still more remote from the real origin of the trouble. An example of such referred pain may be found in the cutaneous pain arising from an inflamed appendix, which often gives rise to a second referred pain in the skin on the opposite side of the abdomen.

The connections and distribution of the efferent nerves may also cause referred pain in the same area of the skin arising from pathological conditions in different organs. Such a result will naturally interfere with correct diagnosis. It may be possible to overcome any confusion by minute delimitation of the supersensitive areas which accompany each undoubted pathological condition.

ANTAGONISTIC SENSORY REFLEXES.

No attempt has been made in this investigation to discover whether different places or modes of excitation can be found which will elicit antagonistic sensory reflexes and thereby inhibit the enhancement of the tactile receptors in the finger under study. Since interfering or antagonistic motor reflexes are known,[1] which make use of the same final common path, analogy would suggest that similar phenomena should characterise all the sensory reflexes.

In vision it is known that two colours can be mixed so as to match in hue a single spectral colour; but the mixed colour is always less saturated than the single, which must therefore have some white light mixed with it in order to make the match perfect in saturation. One of the authors[2] has suggested that this is explained by the fact that the like visual sensory reflexes arising from the two colours in the mixture necessarily use the same final path, and therefore reinforce each other, causing a double production of white light, which the single spectral colour cannot do. White light from an external source must therefore supply the deficiency.

In this phenomenon there is reinforcement of like reflexes. But M'DOUGALL[3] has shown that light of one colour or intensity falling on an area of a retina may be inhibited by light of another colour or intensity falling upon a corresponding area of the other retina. These phenomena of struggle, rivalry, or competition are to be found in uniocular as well as binocular vision. They may be explained by the principle of inhibition, and may be regarded as instances of the occurrence of antagonistic sensory reflexes necessarily making use of the same final path where they interfere. The struggle or fluctuation results from the combined action of fatigue and enhancement.

Since we have no experimental evidence to present regarding antagonistic reflexes in the tactile sensation, we may suggest that this principle finds an illustration in the use of counter-irritants applied in certain bodily disorders.

For example, in bronchitis there is a condition of enhancement of sensitiveness of certain receptor organs in the bronchi which causes the passage of air, or the blood in circulation, to produce irritation. Temporary relief is afforded by coughing, which fatigues the receptors. This in turn produces post-fatigue enhancement, with the result that a vicious cycle is set up, one effect increasing the other until fatigue ultimately produces exhaustion.

This condition may be relieved by applying certain powerful counter-irritants to the skin of the chest. To explain this effect, it must be assumed either that some material must pass from the skin to the bronchi, or that the effect is transferred by nervous action. The latter is by far the more probable. The counter-irritant excites certain receptor end-organs which in turn induce sensory reflexes. These make use of the same efferent paths to the bronchi which are used by the enhancing reflexes arising therefrom. Thus there are two sets of sensory reflexes making use of the same final path. If the reflexes are like, the result is reinforcement and increased distress. If the reflexes are antagonistic, inhibition or interference results, and no enhancing action proceeds to the inflamed bronchi. Coughing quickly fatigues the unenhanced receptors to the point where the existing stimuli are not sufficiently powerful to cause excitation, and the natural restorative processes of the body may then be allowed to heal the inflammation without undue disturbance.

---

[1] SHERRINGTON, "Integrative Action of the Nervous System," pp. 138 and 355.

[2] ALLEN, "The reflex origin of the self light of the retina," Journ. Op. Soc. Amer., 1924, viii. 279.

[3] PARSONS, "Colour Vision," p. 275.

This investigation is one of a series of researches relating to colour vision and the physiology of receptor end-organs now being conducted under the direction of Professor Frank Allen with the financial assistance of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa, to which body we desire to express our thanks.

Department of Physics,
University of Manitoba,
Winnipeg, Canada.
26*th March* 1924.

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THE TACTILE SENSORY REFLEX.

By Frank Allen and Mollie Weinberg. From the Department of Physics, University of Manitoba, Winnipeg. (With three figures in the text.)

(Received for publication, 6th July, 1925.)

In a former communication to this Journal (1) on the tactile sensory reflex, by Allen and Hollenberg, a method of studying the sense of touch was described which was based upon the measurement of the critical frequency of percussion of impulses of air at various pressures and under different conditions of stimulation. Through a fine nozzle a stream of air at measured pressures was directed perpendicularly upon the volar aspect of the terminal phalanx of the index finger of the right hand. The jet of air was interrupted by a sectored disc mounted on the axle of an electric motor, by means of which the steady stream was divided into periodic impulses of any required frequency. At each selected pressure of the air from 1·0 cm. to 5·0 cm. of mercury two critical frequencies of percussion were found at which the interrupted impulses became fused into just continuous sensations. These were interpreted as indicating the existence of a superficial and a deep tactile sensation.

When the measurements were plotted on squared paper it was found that they were both represented by the linear equation

$$D = k \log P + c.$$

in which D is the duration of the impulses at the critical frequency of percussion; P the pressure of the air; and k and c are constants, which have different values for the two sensations.

Each of the graphs consisted of two straight lines of different slopes, which were quite similar to those in this paper, except that only two instead of three branches were found.

Both tactile sensations were shown to be susceptible of depression and enhancement of their sensitiveness by stimuli applied, for the former effect, directly to the part of the finger upon which measurements were made, and for the latter, to the other fingers. It was noticed especially that very light stimulation of the digital measuring surface caused a marked enhancement of its sensitiveness.

In very recent investigations in colour vision, shortly to be published, it has been found by one of the writers (Allen) that changes in the intensity of a colour, when plotted in logarithmic form, were represented by three, and in some cases by four straight lines. It was found also that the underlying cause of the change of slope was a change in the ratio of the magnitudes of the enhancing and depressing nervous impulses, conveyed by sensory reflex action to the receptor organs.

The various senses have been found to be so similar in their behaviour that the same characteristics in the logarithmic intensity graphs were expected to be found in each. An examination of those already obtained in an investigation in the sense of taste (2) showed clearly the threefold linear structure of each of the graphs for the four primary gustatory sensations.

In both vision and taste it was found that stimuli of very low intensities depressed, and of medium intensities enhanced, the sensitiveness of the receptors. In other words, the resulting depression or enhancement was the measure of the excess of one process over the other, both being actively and simultaneously present.

It was anticipated that if in the sense of touch the measurements of the critical frequency of percussion were made for pressures lower than 1·0 cm. of mercury, which, as mentioned above, was the lowest previously employed, a third branch of the graph would be obtained corresponding to intensities of stimulation which caused light-touch enhancement.

The apparatus employed was the same as that used in the former investigation with a very slight rearrangement. For it was speedily found that the finger was not sufficiently sensitive to detect the fusion of the air impulses at such low pressures. The lips, however, proved to be extremely sensitive, and the critical frequency of percussion could be found with the greatest ease and precision. Accordingly, a chin-rest was placed at a suitable height so that the air jet impinged perpendicularly upon the centre of the lower lip. A thin protecting screen was interposed between the face and the rotating metal disc. In all other particulars the arrangements were identical with those described in the paper to which reference has already been made. As in the previous investigation, vaseline was thinly spread over the lip to protect it from the drying action of the air.

In making measurements a constant routine was followed. The air was adjusted to a desired pressure, and the chin placed on the rest so that the lip was in the proper position. The disc was then set in rotation, and its speed increased until the separate tactile impulses just fused into a continuous sensation. At this point the chronograph record was taken from which the value of the critical frequency of percussion was determined.

The range of pressures employed was from 0·4 cm. to 4·6 cm. of mercury.

The normal curves in which the air pressures are plotted with the duration of the impulses at the critical frequency of percussion are given in fig. 1. In logarithmic form they are shown in fig. 2. The experimental measurements are tabulated in Table I. In each figure curve A

TABLE I.

	Press. P.	Duration D. Sec.	Log. P.		Press. P.	Duration D. Sec.	Log. P.
	cm.				cm.		
A	0·48	0·01160	$\bar{1}$·681	B	0·40	0·01140	$\bar{1}$·602
	0·63	·01060	$\bar{1}$·799		0·50	·01040	$\bar{1}$·699
	0·68	·01015	$\bar{1}$·833		0·55	·00990	$\bar{1}$·740
	0·90	·00910	$\bar{1}$·954		0·58	·00972	$\bar{1}$·763
	1·00	·00870	0		0·70	·00860	$\bar{1}$·845
	1·12	·00825	·049		0·98	·00775	$\bar{1}$·991
	1·47	·00750	·167		1·20	·00710	·079
	1·70	·00705	·230		1·30	·00685	·114
	2·10	·00655	·322		1·37	·00650	·137
	2·30	·00625	·362		1·50	·00630	·176
	2·43	·00605	·386		1·70	·00595	·230
	2·70	·00583	·431		2·07	·00530	·316
	2·95	·00548	·470		2·33	·00500	·367
	3·33	·00525	·522		2·50	·00482	·398
	3·75	·00490	·574		2·57	·00472	·410
	4·00	·00475	·602		2·90	·00427	·462
	4·23	·00460	·626		3·33	·00380	·522
	4·37	·00420	·640		4·03	·00315	·605
	4·60	·00390	·663		4·43	·00290	·646
a	1·33	0·00700	·124	*b*	1·05	0·00705	·021
	1·47	·00673	·167		1·45	·00600	·161
	1·86	·00610	·270		1·60	·00582	·204
	1·90	·00592	·279		1·85	·00533	·267
	2·10	·00560	·322		2·00	·00525	·301
	2·47	·00500	·393		2·13	·00500	·328
	3·10	·00415	·491		2·20	·00485	·342
	3·40	·00390	·531		2·28	·00475	·358
					2·52	·00442	·401
					2·64	·00425	·422
					2·70	·00414	·431
					3·40	·00350	·531
c	1·05	0·00675	·021	*d*	1·00	·00770	0
	1·40	·00590	·146		1·06	·00740	·025
	1·77	·00530	·248		1·40	·00632	·146
	1·88	·00505	·274		1·77	·00575	·248
	2·17	·00460	·336		2·30	·00500	·362
	2·33	·00430	·367		2·40	·00495	·380
	2·83	·00390	·452		2·52	·00470	·401
	3·23	·00335	·509		2·57	·00463	·410
	3·50	·00330	·544		2·67	·00460	·427
					3·04	·00410	·483
					3·16	·00396	·500
					3·70	·00340	·568

is the first series of fusion points, and represents the superficial system of tactile sensibility; curve B, the second series of fusion points, represents the deep system. It will be seen that these results confirm those previously obtained by ALLEN and HOLLENBERG.

In fig. 2, curve A is seen to consist of three branches, the changes of slope occurring at the pressures of about 1·0 cm. and 4·0 cm. Curve B is composed of two branches with a change of slope at the pressure 0·8 cm. In all probability this graph also has three branches, the missing one occurring at speeds higher than the capacity of our apparatus to measure. In the former investigation it was found that the changes of slope of the branches of the graphs for the superficial and deep tactile sensations were in opposite directions. This was believed to be due to some characteristic difference in their nature. The graphs in fig. 2, however, show this explanation to be erroneous. For it is now obvious that in the former paper the graph for the superficial sensation consisted of the second and third branches only, while that for the deep sensation consisted of the first and second. From this figure both sensations are seen to behave in the same manner, the deep, however, being more sensitive than the superficial.

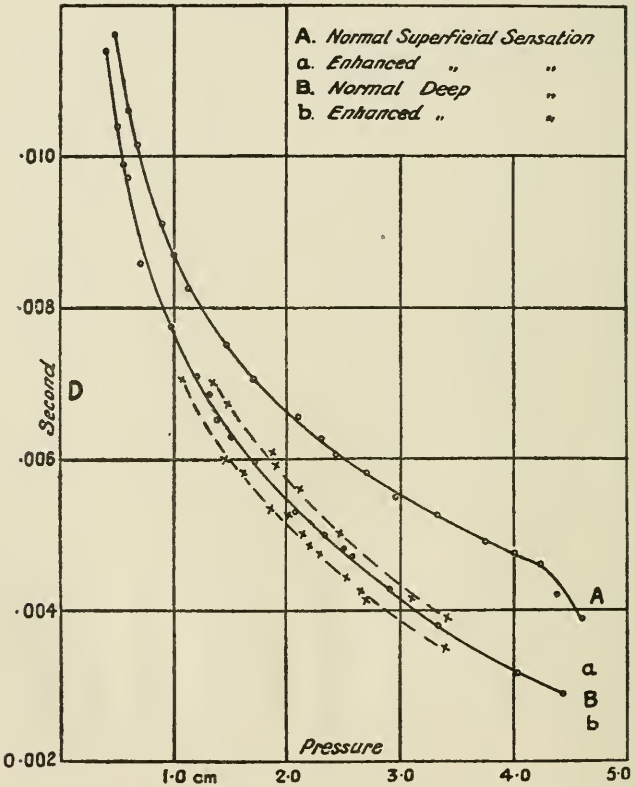

FIG. 1.—Normal curves for the superficial and deep tactile sensations in the lower lip. Enhancement produced by light-touch stimulation of the lower lip.

The second purpose of this investigation was a more detailed study of light-touch enhancement than was made in the former paper. The lower lip, especially the part upon which the measurements were made, was very gently stimulated by passing the tip of a feather lightly over it for about ten or fifteen seconds, and measurements of the critical frequency of percussion immediately taken. The intensity of this

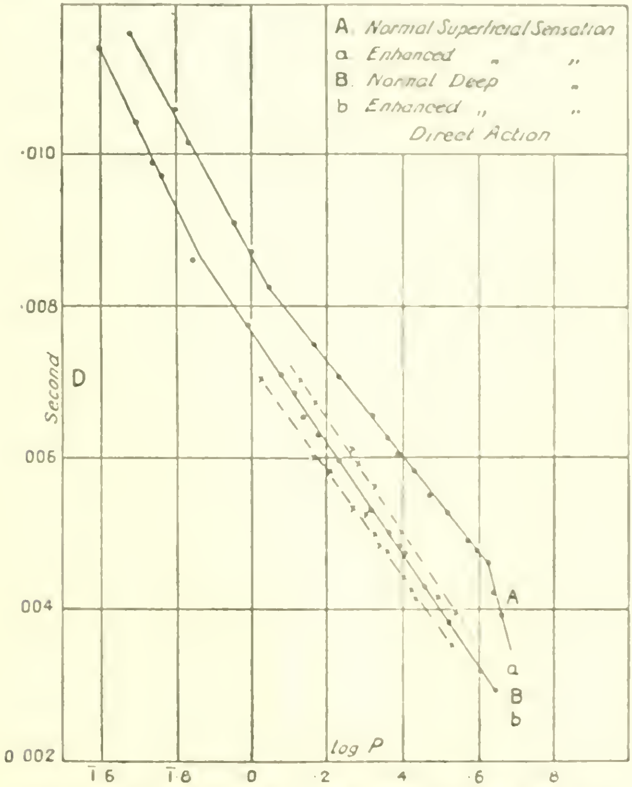

Fig. 2.—The curves of fig. 1 reduced to logarithmic form.

stimulation undoubtedly would represent a pressure in the uppermost branch of the normal logarithmic curve.

The results are shown graphically as curves *a* and *b* in fig. 1 in the direct form, and in fig. 2 in the logarithmic. The continuous lines, A and B, are the normal curves, and the broken lines, *a* and *b*, the enhanced. The measurements are given in the table under the same letters. The lowered position of the curve *a*, below the corresponding normal A, indicates that the superficial tactile sensation has been greatly enhanced by the stimulation; while the much smaller displacement of *b* below its corresponding normal B, shows that the deep tactile sensation also has been enhanced, but only very slightly. The differing degrees of enhancement of the two sensations are to be expected, since the stimulation on account of its very small intensity would affect almost exclusively the receptors close to the surface of the lip. These results also indicate that the two tactile sensations are not independent of each other.

Even though stimulation with the feather was very light, yet some depression or fatigue of the superficial sensation must have occurred. The enhancement measured is, therefore, the excess of that effect over the depression. The enhancement alone may accordingly be expected to be much greater than that obtained by stimulation of the lower lip. After gently stimulating the upper lip in the manner described, a series of measurements of the critical frequency of percussion on the same area of the lower lip was made, which are given in the table under *c* and *d*, and are similarly indicated in fig. 3. It will be noticed that one series of points, *c*, falls exactly on the normal curve B, for the deep tactile sensation. These are indicated by the crosses on that curve The other series of points forms another curve, *d*, below B.

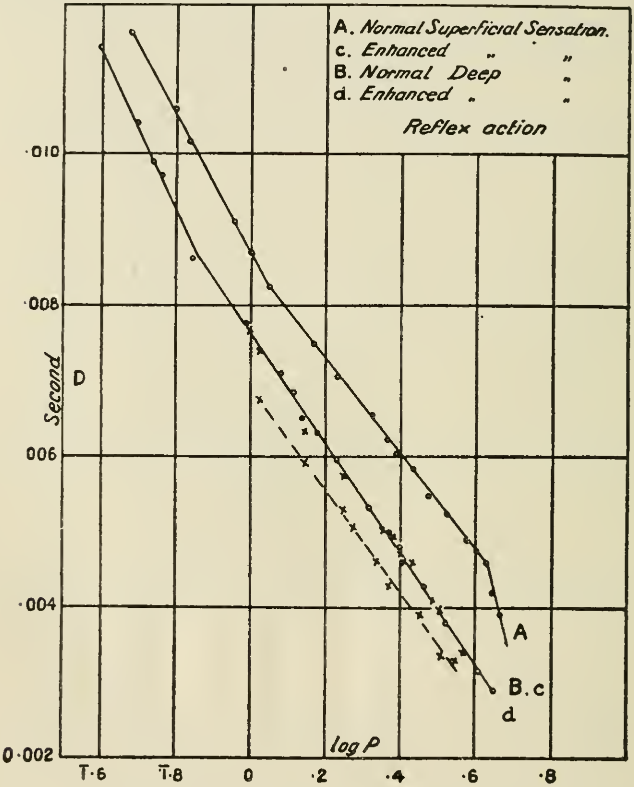

Fig. 3.—Curves showing enhancement of the tactile sensations in the lower lip by light-touch stimulation of the upper lip.

Two interpretations of these results are possible: first, that the coincidence of curve *c* with B represents an enhancement of the superficial tactile sensation greater than that shown in fig. 2, and curve *d* about the same enhancement of the deep tactile sensation as before; second, that the deep tactile sensation in the lower lip has been unaffected by reflex action from the upper, and that curve *d* represents an extraordinary degree of enhancement of the superficial sensation.

In the senses of vision and taste it has always been found that the three primary sensations of the former and the four of the latter are all invariably affected by depression or enhancement of sensitiveness by every stimulus that has been applied. Though it appears somewhat remarkable that the measurements of the enhancement of the superficial sensation should fall with almost perfect exactness upon B for the deep sensation, we are inclined to believe that the stimulation of the upper lip by very light touch has affected the deep system to a greater extent than before, and that the superficial system also has been enhanced to a greater degree than in the former case, since the depressing effect has been reduced to a minimum.

These results are in conformity with the sensory reflex theory which we may thus briefly describe: a stimulus applied to any sensory receptor arouses a sensation in the corresponding central organs, and in addition evokes simultaneously two sets of efferent impulses, one of which enhances and the other depresses the sensitiveness of the receptors of the whole sensory system, the degree of enhancement or depression being the measure of the excess of one process over the other. On this view the sensitivity of the receptors and the state of sensory tonus are normally controlled by the efferent nervous system, which is further controlled by the intensity of the stimulus.

We desire to record our thanks to the Research Council of Canada with whose assistance this investigation has been conducted.

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Synopsis.

In this investigation a method of exact measurement of the intensity of stimulation of the sensations of taste was devised by means of electrolysis of the saliva. The electric current at definite potentials was intermittently applied to the tongue and the critical frequency of gustation measured, *i.e.* the duration of each taste impulse when the interrupted stimuli became fused into continuity.

Four curves were obtained which correspond to, and confirm the existence of, four primary tastes: sweet, salt, sour, and bitter.

The results conformed to a law derived from Fechner's Law, which may be expressed, $\frac{1}{D} = -k \log Q + C$.

The similarity of this law with those obtained in vision, touch, and audition is discussed.

When stimulation of the tongue was produced with gymnemic acid, sugar, salt, acetic acid, and quinine, characteristic depressing and enhancing effects were obtained on all sensations.

The results are in conformity with a theory of sensory reflex action which may be stated thus: an afferent stimulus which produces a sensation also evokes two reflex efferent effects on the entire sense organ, the resulting condition of enhancement or depression at any point being the measure of the excess of one process over the other.

The Normal Sensations.

An examination of the literature on the sense of taste reveals the fact that but little is known of the subject. This is apparent in both the physiological and the psychological fields. The standard treatises on the former science devote to the discussion of this sense from three to four pages, and those on the latter even less. Following is a summary of the present extent of knowledge of the subject, which, it will be observed, is purely qualitative in character.

The gustatory receptors upon the tongue are capable of initiating four primary or fundamental taste sensations: sweet, salt, sour, and bitter. The almost infinite varieties or shades of tastes one is capable of experiencing are made up of combinations of these four in various proportions of intensity, modified, in addition, by sensations resulting from excitation of the end-organs of smell and those of general sensibility, touch, temperature, and pain.

The four primary tastes are generally distributed or localised on the tongue in the following manner: sweet, at the tip; salt, at the sides and towards the tip; sour, at the sides; bitter, at the back or root. There are no well-defined limits of localisation, however, all taste stimuli being capable of perception to a greater or less degree on any portion of the tongue that is sensitive to taste sensations in general.

The probable gustatory end-organs are the taste-buds. These are present in great numbers on the circumvallate and fungiform papillæ embedded in the stratified epithelium on the tongue. Within the taste-bud are a number of elongated cells, each of which contains a large nucleus and ends in a minute hair-like process—the gustatory hair—which projects through an equally minute opening in the bud—the gustatory pore—into the mouth cavity. These cells are considered the true sense cells. Amongst them are the endings of numerous fine nerve fibres. Direct stimulation probably takes place at the gustatory hair, and passes down through the gustatory cell to the nerve fibres among them. The path of the taste impulse from the end-organs to the brain is not definitely known.

Drugs act selectively on the gustatory receptor organs. Gymnemic acid, for example, anæsthetises the sweet taste receptors totally, and the bitter almost completely. Cocaine first causes a diminution of tactile and pain sensibilities; then completely destroys the bitter, then the sweet, and finally the sour taste, while the salt sensation appears to remain unaffected.

Both simultaneous and successive contrast have been observed in the gustatory sensations. As an illustration of the former, it has been found that solutions of salt and sugar applied simultaneously on both sides of the tongue increase to a marked degree the effect of each; and of the latter, that distilled water tastes sweet after dilute acid has been applied to the tongue.

Compensation or complementary phenomena have also been noted. Sweet and bitter stimuli, for example, have a neutralising effect upon each other. This principle is utilised in the common practice of counteracting the bitter taste of coffee by the use of sugar.

The present research is an attempt to subject the gustatory sensations to quantitative investigation. It deals specifically with an application of the method of the critical frequency of interruption of stimulation to the sensations of taste, in an analogous manner to that in which it has been already employed in researches on vision (1), audition (2), and touch (3). It consists in increasing the rapidity of gustatory stimulation of the tongue until fusion of the interrupted sensations just occurs. The time interval between two successive stimulations at this point is determined, and is a measure of the time the taste stimulus persists. In vision, a similar measurement has been termed the critical frequency of flicker of the colour, in sound, the critical frequency of pulsation or flutter of the tone; in touch, the critical frequency of percussion of the tactile stimulus; and now in taste we have termed it, the critical frequency of gustation of the taste stimulus.

The method of intermittent stimulation of the taste sensations requires the application of a stimulus of definite and controlled intensity to one point on the tongue at equal intervals of time, followed by its

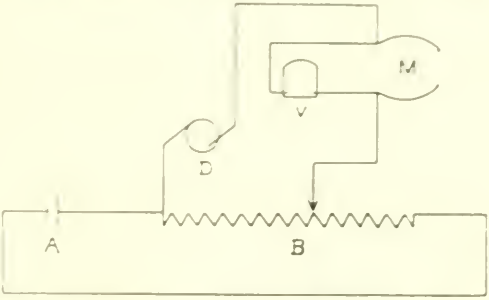

Fig. 1 — Diagram of electrical connections to mouth-piece. A, storage cell; B, potentiometer; D, disc; V, voltmeter; M, mouth-piece.

complete removal, in analogy with flashes of light upon the eye alternating with darkness. To accomplish this by mechanical application of such substances as salt and sugar, for example, is impossible.

The only feasible method of gustatory measurement that occurred to the authors was the employment of the long-known, but hitherto unused, observation that an electric current applied to the tongue arouses the sensation of taste. Intermittent stimulation was effected by electrolysis of the saliva with a periodically interrupted electric current.

A single storage cell supplied the current, which was conducted through a high resistance forming a potentiometer, from which a portion of the current at any desired potential passed through an interrupting disc to a suitable mouth-piece. The arrangement of the apparatus is shown in fig. 1.

The disc was constructed of two discs, one of which was of non-conducting fibre, and the other of copper, both four inches in diameter. Each of these had twenty teeth of equal size. By dovetailing the two discs together, their edges combined to form a circumference of forty equal arcs, alternately conducting and non-conducting. One electrode made continuous contact with the side of the copper disc, and the other pressed upon the smooth sectioned edge. By this means the steady current was converted into periodic electric impulses, each of which lasted for one-fortieth of the time of rotation of the disc, with the same interval of time between successive impulses.

The disc was mounted on the shaft of a small direct-current electric motor, the speed of which was regulated by a rheostat and a leather brake. The critical frequency of gustation was accurately determined by means of a speed counter, also mounted upon the motor shaft, which closed another electric circuit every fiftieth revolution of the shaft, and which was connected, together with a clock beating half-seconds, to a chronograph.

The mouth-piece consisted of two narrow curved strips of spring brass, 2 cm. long, which terminated in brass hemispheres 1·6 mm. in diameter. The strips were held in small blocks of ebonite which were kept 1 cm. apart by pieces of wood inserted in such a manner as to form a small box-like opening 2 cm. long and 1 cm. wide, into which the tip of the tongue extended. The electrodes were silver-plated to minimise the possibility of chemical action with the saliva. A mirror was placed in a suitable position to enable the experimenter to see the electrodes in position on the tongue.

The intensity of stimulation was adjusted and controlled by varying the potential, and was measured by a millivoltmeter connected across the terminals of the mouth-piece. The range employed was 0·16 to 0·70 volt. These limits were self-determined, for potentials below the former value gave no perceptible stimulation, and those above the latter produced muscular twitching.

In making measurements a constant routine was followed. The potentiometer was adjusted to give the desired voltage; the negative terminal of the mouth-piece was placed on a definite spot on the upper surface of the tongue, the positive on a corresponding spot immediately underneath it; the motor circuit was closed and the speed adjusted until the interrupted gustatory stimuli just fused into a continuous sensation. A chronograph record was then taken, from which the critical frequency of gustation was computed. It should be noted that the current was not allowed to run through the tongue continuously until final adjustments were made, but was interrupted every half or whole second in order that the accumulated results of electrolysis, which cannot be removed, might be a minimum. The time of passage of the current for each measurement varied from two to three and a half seconds. An interval of from ten to twenty minutes was allowed between measurements for recovery from any fatigue that might have occurred, and also to permit the products of electrolysis to be diffused. All measurements were made as nearly as possible on the same spot on the right side of the tongue.

It required considerable training of the attention and judgment, as well as of the hands, in automatically making the requisite instrumental adjustments, before observations could be made with confidence and accuracy.

In the course of a month several hundred readings had accumulated, which appeared very irregular and confusing. Since the electric current excites a sour taste, we had anticipated a single curve for that sensation, and had scarcely any hope that a method of obtaining curves for the other gustatory sensations might be found. The result showed that the difficulty was of a completely opposite character.

It was finally decided to plot each of the apparently inconsistent readings individually, with the voltages on the horizontal axis and the time intervals at the critical frequency of gustation on the vertical. To our great surprise and satisfaction it was found that the points fell along four distinct and well-defined curves, with a greater number of points falling on one of them than on any of the others. It thus became quite clear that there were four fusion points of interrupted stimulation for each voltage, that is, the gustatory receptor organs were sensitive in four different degrees to a stimulus of a single intensity. It was found impossible to control the experimental conditions to such an extent that would enable one to determine beforehand upon which curve a point should fall; or, with what degree of sensitiveness the receptors would respond to any definite stimulus. It is thus apparent that the mechanism of taste is more complex or involved than the visual or auditory apparatus, and very much more than the touch receptor organs, which have two independent systems of response to tactile stimulation (3).

On one occasion, while a satisfactory measurement of the critical frequency of gustation was being recorded, it was noticed that complete fusion was no longer obtained. Thereupon the speed of the motor was immediately increased to a new point of fusion without interrupting the record. When the measurements were completed there were found to be two different results which fell on two adjoining curves. It is possible that the electrodes slightly moved, though no such effect was perceptible.

The four curves are shown in fig. 2, and the measurements are given in Table I. These are termed the normal gustatory curves, and represent the averages of from 400 to 500 readings. As shown in the figure, the curves are similar in character, gently sloping upward at low voltages, but with a decided increase of slope and rapid convergence towards a point at high potentials. The duration of the taste sensation at the fusion point is seen to increase with the potential. The positions of the curves upon the diagram indicate their differing sensitivities to the same series of stimuli, their convergence, an approach towards uniform sensitivity at high potentials. The normal curves may be interpreted as proving the existence of four gustatory receptor organs, each responding with specific sensitiveness to one definite primary taste.

The question of the identification of the curves was next considered.

Actual excitation was, of course, with a sour stimulus. The curve upon which the greatest number of points fell, *i.e.* the curve representing the greatest number of responses to the sour stimulus, is in all probability the one indicating the reaction of the sour receptors. This is curve C in fig. 2. Though the identification of the remaining curves had to be postponed until further experimentation was completed, the curves in the figure are marked as finally determined: namely, sweet, A; salt, B; and bitter, D.

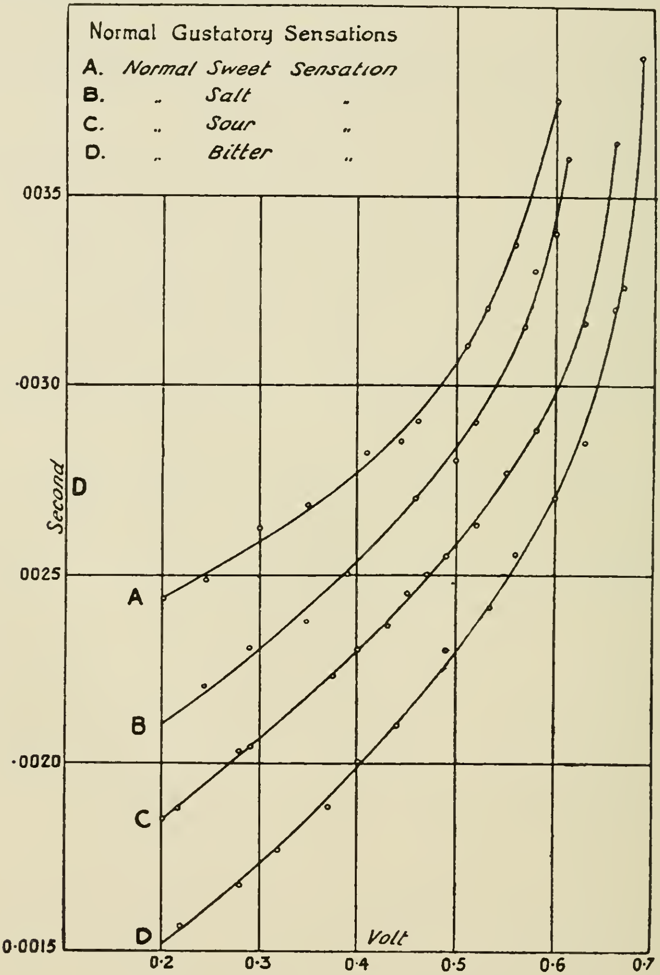

Fig. 2.—Normal gustatory sensations.

Since electrical stimulation of the tongue gives a sour taste and also measurably affects the remaining primary sensations, it is evident that sour is only the predominant taste, as all are involved. In colour vision every colour affects all three sensations, and in consequence is never

TABLE I.—NORMAL CURVES

	Volt V	Duration D = Sec	Log Q = Log VD	1/D		Volt V	Duration D = Sec	Log Q = Log VD	1/D
A	0·200	0·00243	$\bar{4}$·687	412	C	0·200	0·00185	$\bar{4}$·568	541
	·245	·00248	$\bar{4}$·784	403		·215	·00188	$\bar{4}$·606	532
	·300	·00262	$\bar{4}$·895	382		·280	·00203	$\bar{4}$·754	493
	·350	·00268	$\bar{4}$·972	373		·290	·00204	$\bar{4}$·772	490
	·410	·00282	$\bar{3}$·061	355		·375	·00223	$\bar{4}$·922	448
	·445	·00285	$\bar{3}$·104	351		·400	·00230	$\bar{4}$·964	435
	·460	·00290	$\bar{3}$·124	345		·430	·00236	$\bar{3}$·009	424
	·510	·00310	$\bar{3}$·199	323		·450	·00245	$\bar{3}$·041	408
	·530	·00320	$\bar{3}$·231	313		·470	·00250	$\bar{3}$·072	400
	·560	·00337	$\bar{3}$·277	297		·490	·00255	$\bar{3}$·097	392
	·600	·00375	$\bar{3}$·352	267		·520	·00263	$\bar{3}$·137	380
						·550	·00277	$\bar{3}$·182	361
						·580	·00288	$\bar{3}$·223	347
						·630	·00316	$\bar{3}$·299	316
						·660	·00364	$\bar{3}$·380	275
B	0·230	0·00214	$\bar{4}$·692	467	D	0·220	0·00157	$\bar{4}$·538	637
	·290	·00230	$\bar{4}$·824	435		·280	·00167	$\bar{4}$·670	599
	·350	·00237	$\bar{4}$·919	422		·320	·00177	$\bar{4}$·753	565
	·390	·00250	$\bar{4}$·989	400		·370	·00188	$\bar{4}$·843	532
	·460	·00270	$\bar{3}$·093	370		·400	·00200	$\bar{4}$·903	500
	·500	·00280	$\bar{3}$·146	357		·440	·00210	$\bar{4}$·966	476
	·520	·00290	$\bar{3}$·179	345		·490	·00230	$\bar{3}$·053	435
	·570	·00315	$\bar{3}$·255	317		·535	·00241	$\bar{3}$·111	415
	·580	·00330	$\bar{3}$·281	303		·560	·00255	$\bar{3}$·155	392
	·600	·00340	$\bar{3}$·310	294		·600	·00270	$\bar{3}$·210	370
	·610	·00360	$\bar{3}$·342	278		·630	·00285	$\bar{3}$·255	351
						·660	·00320	$\bar{3}$·324	313
						·670	·00326	$\bar{3}$·339	307
						·685	·00387	$\bar{3}$·426	258

perceived fully saturated. So in the gustatory sense, no taste is ever experienced alone. We do not know, apparently, what a perfectly saturated taste is.

The voltage has hitherto been referred to as the intensity of the stimulus. This, however, is not strictly the case. In the process of electrolysis, according to Faraday's Law, the amount of any ion produced is proportional to the quantity of electricity flowing through the electrolyte. The quantity of electricity at any voltage may, therefore, be regarded as the true measure of the intensity of the sour stimulus.

According to Ohm's Law

$$i = \frac{V}{r},$$

where i is the current through the tongue, V the potential difference, and r the resistance of the tongue between the electrodes, which may be considered constant.

Multiplying both sides of the equation by D, the time during which the current is flowing, we have

$$iD = \frac{1}{r} . VD.$$

Now Q, the quantity of electricity, is measured by the product of the current and the time, therefore

$$Q = iD = \frac{1}{r} . VD = A . VD$$

where A is the constant $\frac{1}{r}$.

Taking logarithms, we have,

$$\log Q = \log (VD) + \log A,$$

where log A is a constant.

The quantities V and D are recorded at each reading. We thus have experimental records from which the values of Q, the true measure of the intensity of the stimulus, can be computed. Any relation existing between the intensity of the stimulus and its duration at the critical frequency of gustation must, therefore, be sought between the quantities Q and D.

In attempting to discover the mathematical law connecting these quantities, several relations were tried without success. No linear relation involving either D, directly, or log V was found to hold. It was finally discovered that the normal readings for the four sensations conformed to the law

$$\frac{1}{D} = -k \log Q + C,$$

which is equivalent to

$$\frac{1}{D} = -k \log (VD) + k \log A,$$

since k and log A are constants.

In this equation $\frac{1}{D}$ is the reciprocal of the duration of the stimulus at the critical frequency of gustation, Q is the quantity (coulomb) of electricity, and k and C are constants which depend on the nature of the gustatory receptors and on the method of stimulation and measurement.

The curves obtained by plotting the reciprocals of D with the values of log Q, *i.e.* log (VD), are shown in fig. 3. The data are given in Table I. The graphs are straight lines with two abrupt changes of slope in the same direction in each, which occur at approximately the same values of the intensity of stimulation. The convergence of all the graphs towards a point at the high intensities is here still more marked than in fig. 2. Since the vertical co-ordinates in fig. 2 are the values of D, and those in fig. 3 are the reciprocals of this quantity, the order of the graphs in the latter figure is reversed.

Consideration of the significance of the three branches of each of the graphs is postponed until further experiments are described.

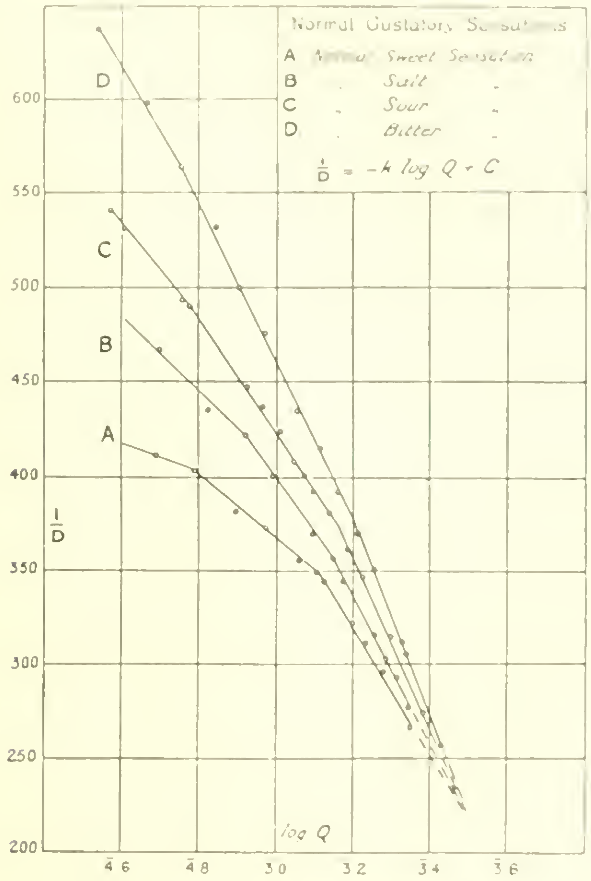

FIG. 3.—Normal gustatory sensations.

The equation to the graphs in fig. 3, which has been found above, is of the same type as the equations obtained in similar investigations in vision, touch, and audition, to which reference has been made.

In vision, graphs have been obtained recently, like that in fig. 4, which consist of three branches. These have not hitherto been published. They conform to the equation

$$\frac{1}{D} = k \log I - C,$$

where I is the luminosity of the light stimulus, k and C are constants.

and D is the measurement of the critical frequency of flicker. The three branches of the graph conform to this equation by changing the values of the constants. This equation in colour vision is known as the Ferry-Porter Law.

In audition a similar equation has also been found by the writers to apply to the graph which is shown in fig. 4, viz.—

$$D = k \log P + C,$$

where P is the pressure of the air producing the tone, to which the intensity of the sound is proportional, and D is the measurement of the critical frequency of pulsation or flutter of the tone.

In touch the same equation also appears, as was found by ALLEN and HOLLENBERG,

$$D = -k \log P + C,$$

where P is the pressure of the air jet, and D the measurement of the critical frequency of percussion. The graph, shown in fig. 4, which has recently been obtained by one of the writers (WEINBERG) (8), has three branches instead of two, which were found by ALLEN and HOLLENBERG.

The four equations may with advantage be brought together for comparison :—

$$\frac{1}{D} = k \log I + C \qquad \text{(Vision)}$$

$$\frac{1}{D} = -k \log Q + C \qquad \text{(Taste)}$$

$$D = k \log P + C \qquad \text{(Audition)}$$

$$D = -k \log P + C \qquad \text{(Touch)}$$

The equation for vision has been derived by PEDDIE (4) from Fechner's Law, and we may conclude with confidence that the other equations may be similarly obtained from it. Fechner's Law has been believed to apply only to a moderate range of intensities of stimulation and to be invalid for both very low and very high values. The graphs with their three branches, however, show that Fechner's Law does apply throughout the whole range, but for this purpose three sets of constants are necessary. The bearing of the above equations on Fechner's Law has been quite fully discussed in a former paper (3), and need not be repeated here.

Since in the four senses studied the same law applies, we may generalise for all sensory actions by saying that the persistence of a sensory stimulus on its receptor varies either directly or inversely as the logarithm of its intensity. The change of slope of the curves in the four sensations indicates that at some definite intensity of stimulation there is a definite change in the sensitivity of the receptors. In a former paper (3) two suggestions were made to account for this phenomenon. First, the change may be in the receptor organs proper, which would indicate that at a definite intensity of stimulation their sensitivity becomes greater or less than before. Second, the nerve impulses may have a freer or a more hindered passage through the synaptic resistance of the reflex arc when this critical intensity is exceeded.

The investigations on vision, which are now being conducted by one of the writers (ALLEN), indicate that the first of these is correct, and also lay bare the underlying cause of the phenomenon. For when a stimulus is applied to any receptor, not only does a sensation result, but in addition two sets of reflex impulses are simultaneously generated or released and conducted from the cortical centres to the receptors, one of which causes depression (inhibition) of their sensitivity, and the

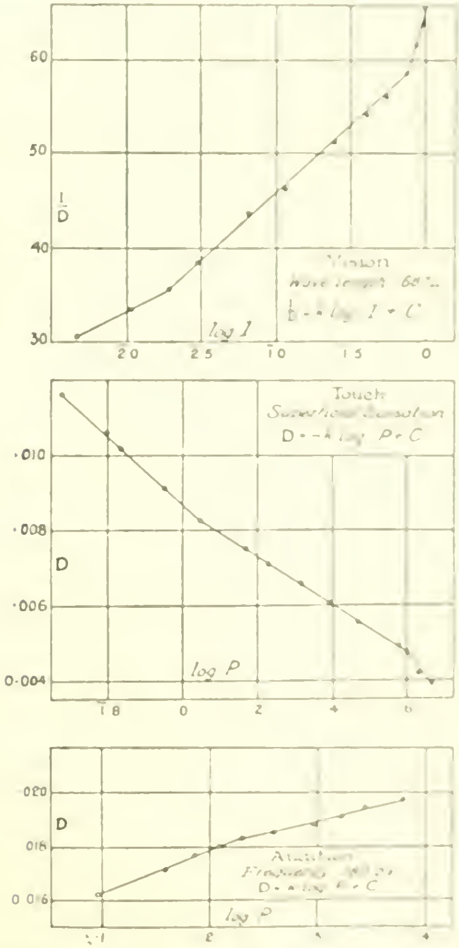

FIG. 4.—Graphs showing differences in responsiveness to stimulation of varying intensities in vision, touch, and audition.

other enhancement (facilitation). Through one range of intensities depression exceeds enhancement, and through another enhancement exceeds depression. The stimulus whose intensity corresponds to the point where the slope changes excites both depression and enhancement equally.

It is interesting to compare the smartness of response of the four sensoria so far studied as measured by the critical frequency method. The time that light persists on the retina at the critical frequency of flicker varies from 0·013 to 0·045 second; the corresponding values in audition are from 0·0127 to 0·0215 second; in touch from 0·0024 to 0·0089 second; and in taste from 0·0015 to 0·0040 second. It is thus seen that the organ of taste is smarter in its response than the others, then follows touch, then audition, and finally vision.

Effects of Stimulation.

The problem of the identification of each normal curve with its primary taste may now be considered. As stated above, since actual excitation was with a sour stimulus, and the greatest number of points fell on curve C, fig. 2, that curve was taken to represent the sour taste. Three curves thus remained to be identified.

It is known that gymnemic acid has a temporary anæsthetising effect upon the sweet and bitter receptors. Application of this drug to the tongue should, therefore, eliminate the two curves corresponding to these tastes. After some trouble a few grams of powdered gymnemic acid were obtained, from which a one-half per cent. solution was prepared. This solution was lightly applied to that portion of the tongue upon which measurements were made, with a little ball of absorbent cotton on the end of a glass rod. The substance was kept on the tongue for about a minute, after which the mouth was quickly rinsed with water at the temperature of the mouth, and a measurement of the critical frequency of gustation immediately taken. A rest of fifteen minutes between readings was allowed for the tongue to regain its normal condition.

The results are given in Table II., and are shown graphically in fig. 5. The continuous curves A, B, C, and D, through the circles, are the normals, and the broken line graphs through the crosses are the results obtained after application of the gymnemic acid. The figure shows two complete curves, *b* and *c*, and also a portion of another, *d*, at the higher potentials. The complete absence of one curve and the partial absence of another at low intensities may be taken to indicate the action of gymnemic acid in anæsthetising both the sweet and the bitter taste receptors, the latter, however, being subject to a forced response by stimulations at the higher intensities.

The two curves, *b* and *c*, do not coincide with any two normals, but are elevated above them. This indicates fatigue or depression of the receptors, and is to be expected ; for although we know that gymnemic acid does not destroy the activity of the sour and salt receptors, it probably must have a highly depressing effect upon their sensitivity.

We know that the incomplete curve *d* shows the effect of gymnemic acid on the bitter taste, and that it is elevated slightly above the normal curve D. This affords evidence that curve D represents the normal response of the receptors for the bitter taste. From previous considerations we know that C is the curve for sour, and that the sour taste is not destroyed by gymnemic acid. One of the new curves should, therefore, represent the depressed sour taste, and, consequently, be elevated above C. Curve *c*, while elevated above both C and B, evidently represents the former. Curve *b* must, therefore, represent the depressed salt taste, which normally is either A or B. Judging from the amount of elevation of *c* above C, it is reasonable to suppose that *b* is the elevated position of B ; which, therefore, is the normal curve for the salt sensation, and A for the sweet. This tentative identification of the normal curves was subsequently confirmed by other experiments. The degree of fatigue or depression of the taste receptors for the salt and sour sensations should not cause wonder, when one considers the powerful depressing

TABLE II.—STIMULATION WITH 0·5 PER CENT. SOLUTION OF GYMNEMIC ACID.

	Volts	Duration (D = Sec.)	Log Q (Log VD)	1/D
b	0·215	0·00260	$\bar{4}$·747	385
	·295	·00280	$\bar{4}$·917	357
	·340	·00290	$\bar{4}$·994	345
	·420	·00300	$\bar{3}$·041	333
	·475	·00315	$\bar{3}$·176	317
	·525	·00343	$\bar{3}$·255	292
	·590	·00397	$\bar{3}$·369	252
	·610	·00420	$\bar{3}$·408	245
c	0·205	0·00220	$\bar{4}$·654	455
	·320	·00240	$\bar{4}$·885	417
	·400	·00258	$\bar{3}$·013	388
	·525	·00294	$\bar{3}$·188	340
	·565	·00312	$\bar{3}$·246	321
	·620	·00347	$\bar{3}$·332	288
	·655	·00378	$\bar{3}$·395	265
d	0·480	0·00230	$\bar{3}$·041	435
	·550	·00255	$\bar{3}$·146	392
	·645	·00300	$\bar{3}$·288	333
	·670	·00345	$\bar{3}$·364	290
	·700	·00430	$\bar{3}$·479	233

or inhibiting effect such a drug must have on an organ as delicate and sensitive as that of taste.

It is clear from the figure that there is a progressive increase in elevation of the fatigue curves as we ascend the series of normal curves in the order of decreasing sensitivity—bitter, sour, salt. This phenomenon shows that the anæsthetising effect of the acid is greater as the

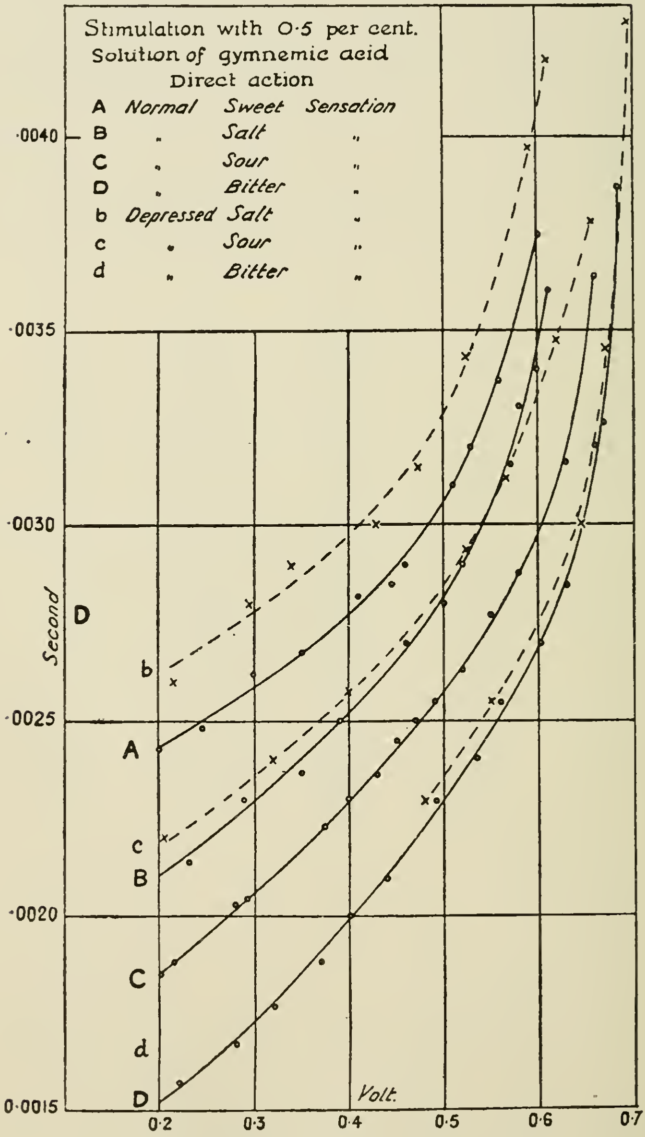

FIG. 5.—Direct action of gymnemic acid.

sensitivity of the receptors becomes less, and that it has its action on the end-organs of taste themselves. If, therefore, the effect of the acid on the sweet receptors were the same in its nature as in the other tastes, the corresponding fatigue curve would be elevated still higher above the normal curve A. The absence of such a curve may, therefore, be interpreted as indicating that the complete anæsthesia of the sweet sensation, due to gymnemic acid, is the result of an excessive depression or inhibition of the activity of these receptors.

The experiments with gymnemic acid have thus been very instructive in giving quantitative confirmation of the fact that gymnemic acid destroys the sensitivity of the sweet taste and partially that of bitter. They have also enabled us to identify quite conclusively the normal curves, and have given some insight into the probable nature of the action of gustatory stimuli upon the taste receptors.

After the identification of the curves was completed we obtained further confirmation in HOWELL's table of the threshold values of the four primary tastes (5):—

Sweet (sugar)—0·5 gram in 100 c.c. of water, detectable on tip of tongue.

Salt (NaCl)—0·25 gram in 100 c.c. of water, detectable on tip of tongue.

Acid (HCl)—0·007 gram in 100 c.c. of water, detectable on border of tongue.

Bitter (quinine)—0·00005 gram in 100 c.c. of water, detectable on root of tongue.

The order of sensitivity of the gustatory receptors exhibited by the normal curves is, therefore, in complete agreement with the order of threshold sensitivity.

A series of experiments was next undertaken to determine the effects of stimulation of the region of the right side of the tongue, upon which the measurements were made, with bisulphate of quinine, acetic acid, sodium chloride, and sugar. This type of stimulation is termed "direct action," in order to distinguish it from stimulation of the left side of the tongue, which is referred to later as "reflex action."

In the same manner as with gymnemic acid, a one eighth per cent. solution of bisulphate of quinine at the temperature of the mouth was applied so as to give direct action of the stimulus upon the tongue. It was kept in place for about forty-five seconds, as apparently in that time the maximum effect was produced. The mouth was then quickly rinsed with water at the same temperature, and a measurement of the critical frequency of gustation made. The process was repeated over the range of voltages used for the normal curves.

The readings are given in Table III., and the corresponding curves are shown in fig. 6. In this and in all similar figures the normal curves are shown as continuous lines through the circles, and lettered A, B, C, and D, which correspond respectively to the sweet, salt, sour, and bitter sensations.

The curves obtained after stimulation are in broken lines, with the points marked by the crosses. They are designated by the corresponding small letters, *a*, *b*, *c*, *d*, etc.

On referring to the figure, it is found that four new curves have resulted from stimulation with quinine. The curves are all elevated above the normals, which indicates fatigue, or, more properly, depression of sensitiveness of the receptor organs of each taste sensation. The curve for the salt sensation *b* does not extend the full length, no readings having been recorded in the upper portion.

Table III.—Stimulation with 0·125 per cent. Solution of Quinine Bisulphate.

	Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.		Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.
a	0·280	0·00270	$\bar{4}\cdot879$	370	*c*	0·230	0·00205	$\bar{4}\cdot674$	488
	·320	·00280	$\bar{4}\cdot952$	357		·280	·00217	$\bar{4}\cdot784$	461
	·375	·00287	$\bar{3}\cdot033$	348		·310	·00225	$\bar{4}\cdot844$	444
	·410	·00295	$\bar{3}\cdot083$	339		·370	·00238	$\bar{4}\cdot945$	420
	·450	·00305	$\bar{3}\cdot137$	328		·410	·00243	$\bar{4}\cdot998$	412
	·475	·00320	$\bar{3}\cdot182$	313		·440	·00255	$\bar{3}\cdot049$	392
	·490	·00327	$\bar{3}\cdot204$	306		·475	·00268	$\bar{3}\cdot104$	373
	·530	·00332	$\bar{3}\cdot246$	301		·510	·00273	$\bar{3}\cdot143$	366
	·550	·00345	$\bar{3}\cdot279$	290		·560	·00289	$\bar{3}\cdot210$	346
	·560	·00387	$\bar{3}\cdot336$	259		·590	·00320	$\bar{3}\cdot276$	313
						·630	·00362	$\bar{3}\cdot358$	276
						·650	·00380	$\bar{3}\cdot393$	263
b	0·190	0·00221	$\bar{4}\cdot623$	452	*d*	0·185	0·00175	$\bar{4}\cdot511$	571
	·255	·00238	$\bar{4}\cdot783$	420		·240	·00183	$\bar{4}\cdot642$	546
	·310	·00250	$\bar{4}\cdot889$	400		·260	·00185	$\bar{4}\cdot682$	541
	·370	·00260	$\bar{4}\cdot983$	385		·300	·00200	$\bar{4}\cdot778$	500
	·400	·00270	$\bar{3}\cdot033$	370		·390	·00217	$\bar{4}\cdot927$	461
	·460	·00281	$\bar{3}\cdot111$	356		·415	·00220	$\bar{4}\cdot960$	455
	·495	·00296	$\bar{3}\cdot167$	338		·445	·00228	$\bar{3}\cdot004$	439
						·520	·00250	$\bar{3}\cdot114$	400
						·550	·00264	$\bar{3}\cdot161$	379
						·580	·00275	$\bar{3}\cdot204$	364
						·600	·00285	$\bar{3}\cdot233$	351
						·630	·00300	$\bar{3}\cdot276$	333
						·635	·00324	$\bar{3}\cdot314$	309
						·670	·00370	$\bar{3}\cdot394$	270
						·680	·00420	$\bar{3}\cdot456$	238

From this figure the conclusion may be drawn that stimulation with quinine of the strength used depresses all four gustatory sensations to an apparently equal extent. It is also to be inferred that the sensations are not independent of each other.

The sour stimulus used was a 1½ per cent. solution of acetic acid. This was applied directly in the same manner as described. The readings are given in Table IV., and the corresponding curves are in fig. 7. This shows that the salt, sour, and bitter receptors are depressed in sensitiveness, while the sweet sensation is enhanced. This is proved

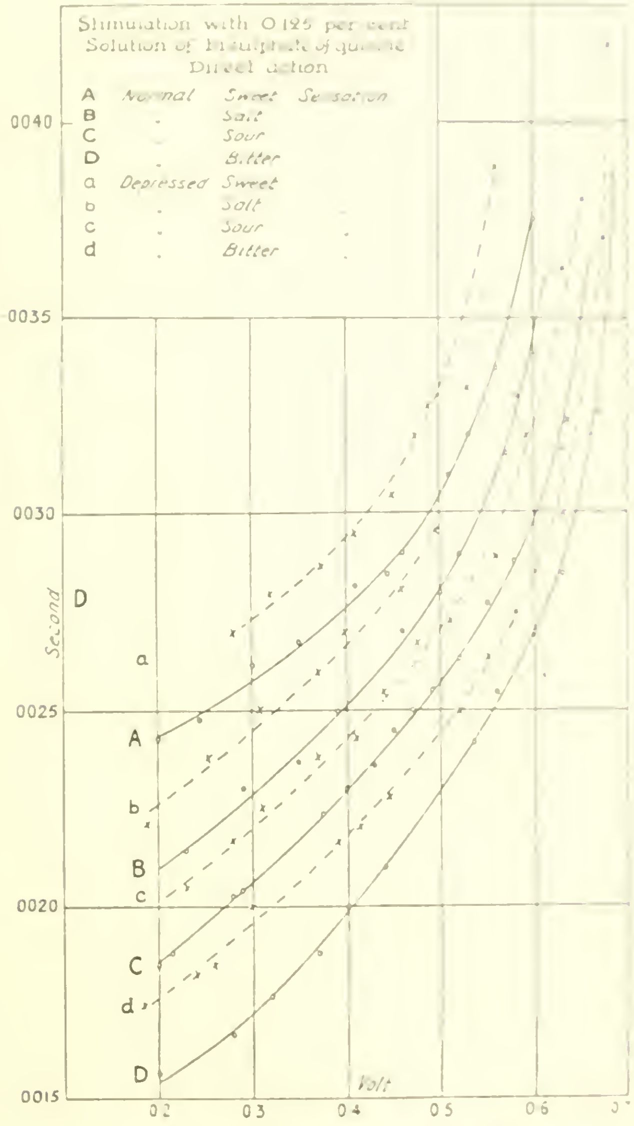

FIG. 6.—Direct action of bitter stimulus.

by the curve *a* falling below the corresponding normal A. It may be remarked that the curve *c* represents thirty individual readings, and the curve *b* only fourteen. As before remarked, the selection of curves or tastes for any measurement cannot be predetermined. The results are obtained apparently only by chance. In this case the distribution of forty-four readings occurred as stated. This quite conclusively identifies *c* as the depressed curve for the sour taste. It is quite possible, however, that curve *a* represents the depressed salt sensation, and curve *b* the enhanced sweet. The interchange of letters for these two curves would not involve any difference in the character of the action upon the receptors, but would only denote a less intense degree of depression and enhancement of the salt and sweet sensations respectively.

Table IV.—Stimulation with 1·5 per cent. Solution of Acetic Acid.

	Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.		Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.
a	0·240	0·00228	$\bar{4}$·738	439	*c*	0·235	0·00208	$\bar{4}$·689	481
	·250	·00230	$\bar{4}$·760	435		·275	·00215	$\bar{4}$·772	465
	·260	·00233	$\bar{4}$·782	429		·300	·00223	$\bar{4}$·825	448
	·300	·00240	$\bar{4}$·857	417		·320	·00230	$\bar{4}$·867	435
	·380	·00254	$\bar{4}$·985	394		·360	·00240	$\bar{4}$·937	417
	·450	·00274	$\bar{3}$·090	365		·380	·00243	$\bar{4}$·965	412
	·580	·00323	$\bar{3}$·272	310		·400	·00245	$\bar{4}$·991	408
	·590	·00340	$\bar{3}$·303	294		·425	·00254	$\bar{3}$·033	394
	·600	·00365	$\bar{3}$·340	274		·485	·00274	$\bar{3}$·121	365
						·505	·00277	$\bar{3}$·146	361
						·555	·00298	$\bar{3}$·217	336
						·585	·00320	$\bar{3}$·272	313
						·610	·00325	$\bar{3}$·297	308
						·625	·00348	$\bar{3}$·338	287
b	0·220	0·00244	$\bar{4}$·730	410	*d*	0·210	0·00180	$\bar{4}$·577	556
	·350	·00263	$\bar{4}$·964	380		·280	·00188	$\bar{4}$·721	532
	·385	·00272	$\bar{3}$·021	368		·310	·00190	$\bar{4}$·770	526
	·420	·00279	$\bar{3}$·068	358		·380	·00205	$\bar{4}$·892	488
	·470	·00290	$\bar{3}$·134	345		·460	·00232	$\bar{3}$·029	431
	·480	·00295	$\bar{3}$·152	339		·510	·00254	$\bar{3}$·114	394
	·540	·00317	$\bar{3}$·233	315		·560	·00268	$\bar{3}$·176	373
	·570	·00340	$\bar{3}$·288	294		·600	·00295	$\bar{3}$·248	339
	·595	·00400	$\bar{3}$·377	250		·615	·00305	$\bar{3}$·274	328
						·655	·00328	$\bar{3}$·332	305
						·670	·00349	$\bar{3}$·369	287
						·680	·00393	$\bar{3}$·427	254

The salt stimulus employed was a 10 per cent. solution of sodium chloride. The measurements are given in Table V., and the corresponding curves in fig. 8. With this stimulus it is found that the bitter sensation *d* is depressed, the sour sensation *c* is depressed, the salt sensation *b* is greatly depressed, but the sweet sensation *a* is enhanced. This last curve, *a*, is remarkable for the complete absence of the middle portion, only the two ends of the curve being present. More peculiar still, an intermediate portion of a curve, *c*, with no points at either high or low potentials, appeared below curve D. This seemed at first to fit nowhere in particular, and was regarded at the time as an anomalous effect. It was soon suspected, however, that curve *c* was the missing portion of curve *a*, shifted abruptly far down on the graph. Closer examination showed that portions of the two curves overlapped at the higher potentials. It must be remembered, however, that it is not the voltage but the quantity of electricity which is the true measure of the intensity of the stimulus. On transforming the co-ordinates of the two

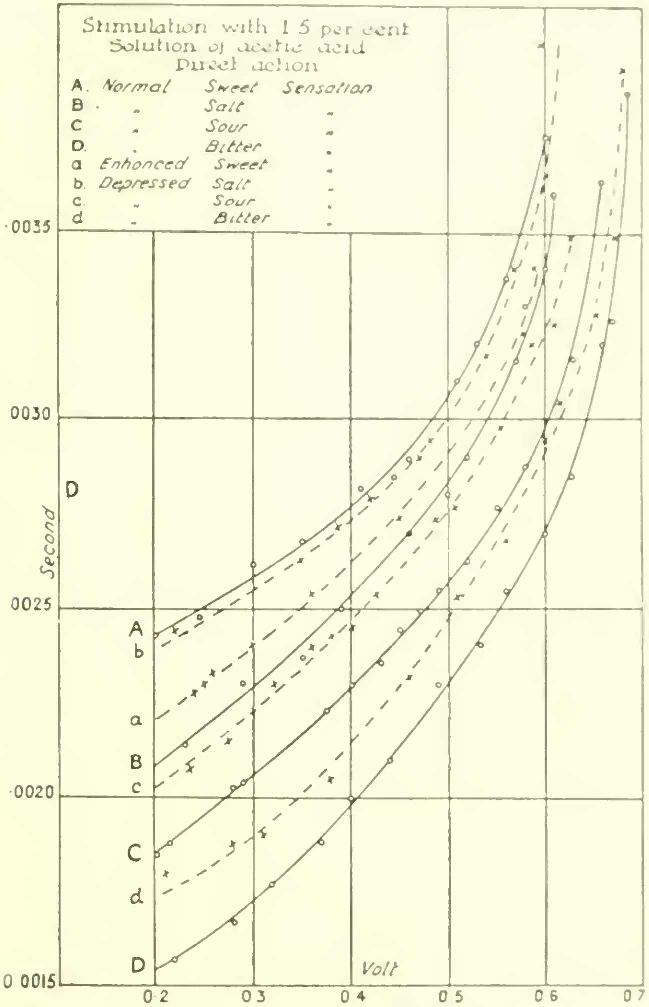

Fig. 7.—Direct action of sour stimulus.

curves from V and D to log Q and the reciprocal of D, it was found that curve *e* fell exactly in the vacant portion of curve *a*, except for the vertical displacement. This is shown in an inset in fig. 13. The abrupt elevation of curve *e* on this graph indicates an extraordinarily enhanced sensitiveness of the sweet receptors, caused by the salt solution, within the narrow range of intensities denoted by the curve. The writers at present are unable to offer any explanation of this isolated occurrence. The phenomenon is no doubt significant, since it indicates that the receptor organs may become peculiarly sensitive to stimuli within narrow intensity limits.

TABLE V.—STIMULATION WITH 10 PER CENT. SOLUTION OF SODIUM CHLORIDE.

	Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.		Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.
a	0·290	0·00268	$\bar{4}$·890	373	*c*	0·160	0·00195	$\bar{4}$·494	513
	·365	·00276	$\bar{3}$·004	362		·220	·00198	$\bar{4}$·639	505
	·380	·00278	$\bar{3}$·025	360		·270	·00204	$\bar{4}$·741	490
	·425	·00288	$\bar{3}$·086	347		·370	·00228	$\bar{4}$·926	439
	·460	·00300	$\bar{3}$·140	333		·400	·00235	$\bar{4}$·973	426
	·500	·00310	$\bar{3}$·190	323		·410	·00242	$\bar{4}$·997	413
	·525	·00320	$\bar{3}$·225	313		·450	·00255	$\bar{3}$·061	392
	·580	·00360	$\bar{3}$·320	278		·480	·00260	$\bar{3}$·097	385
	·600	·00413	$\bar{3}$·394	242		·540	·00277	$\bar{3}$·176	361
						·595	·00302	$\bar{3}$·255	331
						·635	·00360	$\bar{3}$·360	278
b	0·225	0·00225	$\bar{4}$·704	444	*d*	0·170	0·00170	$\bar{4}$·461	588
	·300	·00242	$\bar{4}$·861	413		·230	·00174	$\bar{4}$·602	575
	·365	·00253	$\bar{4}$·965	395		·300	·00190	$\bar{4}$·756	526
	..	..	..	..		·410	·00215	$\bar{4}$·945	465
	·575	·00325	$\bar{3}$·277	308		·430	·00222	$\bar{4}$·980	450
	·610	·00365	$\bar{3}$·348	274		·460	·00225	$\bar{3}$·017	444
						·500	·00249	$\bar{3}$·097	402
						·560	·00260	$\bar{3}$·164	385
						·630	·00295	$\bar{3}$·270	339
						·665	·00317	$\bar{3}$·324	315
						·680	·00380	$\bar{3}$·412	263
e	0·525	0·00203	$\bar{3}$·025	493					
	·595	·00237	$\bar{3}$·149	422					
	·640	·00259	$\bar{3}$·220	386					
	·660	·00280	$\bar{3}$·267	357					

The sweet stimulus first employed was a 20 per cent. solution of white granulated sugar. Two other strengths of solution were also used. All the measurements are given in Table VI., and the corresponding curves in fig. 9. This figure is more complex than the others, as it contains twelve curves. They may easily be distinguished, however, without confusion, and their interpretation is of the greatest importance.

With the 20 per cent. solution the curves *a*, *b*, *c*, and *d* resulted, all of which are below their respective normal curves designated by the corresponding capital letters. This indicates that all four gustatory receptor organs are enhanced in sensitiveness. Even the sweet sensation itself

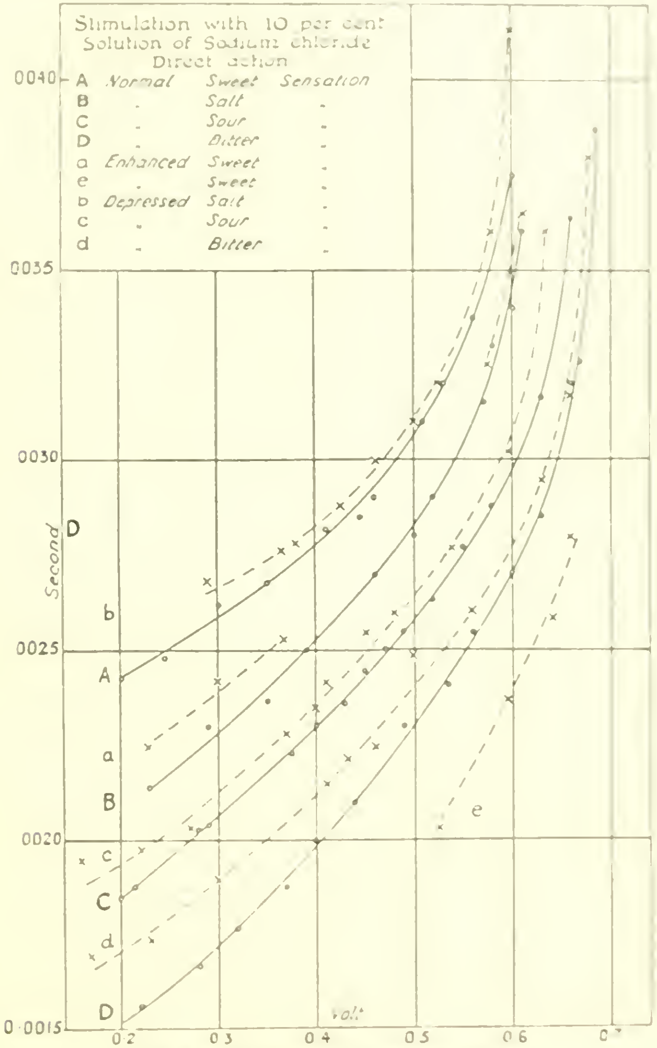

Fig. 8.—Direct action of salt stimulus.

is enhanced. This result seemed at first inconsistent with the general results previously obtained. With bitter, the four sensations were depressed; with acetic acid and salt, the sweet sensation was enhanced, and the remainder depressed.

In preliminary experiments with sugar it was noticed that the curve *h*, which was then obtained, showed by its elevation above A a decided

TABLE VI.—STIMULATION WITH SUGAR.

	Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.		Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.
			20 per cent. solution.						
a	0·180	0·00235	$\bar{4}$·626	426	*c*	0·245	0·00190	$\bar{4}$·631	526
	·290	·00243	$\bar{4}$·848	413		·290	·00205	$\bar{4}$·775	488
	·345	·00256	$\bar{4}$·946	391		·355	·00213	$\bar{4}$·879	469
	·385	·00264	$\bar{3}$·009	379		·370	·00220	$\bar{4}$·911	455
	·420	·00272	$\bar{3}$·057	368		·410	·00230	$\bar{4}$·975	435
	·450	·00279	$\bar{3}$·100	358		·430	·00235	$\bar{3}$·004	426
	·470	·00282	$\bar{3}$·124	355		·475	·00246	$\bar{3}$·068	407
	·480	·00288	$\bar{3}$·140	347		·495	·00251	$\bar{3}$·093	398
	·520	·00302	$\bar{3}$·196	331		·520	·00254	$\bar{3}$·121	394
	·550	·00320	$\bar{3}$·246	313		·550	·00265	$\bar{3}$·164	377
	·575	·00335	$\bar{3}$·286	299		·565	·00277	$\bar{3}$·196	361
	·600	·00360	$\bar{3}$·334	278		·590	·00285	$\bar{3}$·225	351
						·610	·00293	$\bar{3}$·253	341
						·630	·00305	$\bar{3}$·283	328
						·640	·00315	$\bar{3}$·305	317
						·655	·00343	$\bar{3}$·352	292
b	0·240	0·00205	$\bar{4}$·692	488	*d*	0·305	0·00165	$\bar{4}$·702	606
	·310	·00220	$\bar{4}$·834	456		·330	·00168	$\bar{4}$·744	595
	·335	·00225	$\bar{4}$·877	444		·360	·00180	$\bar{4}$·835	556
	·365	·00237	$\bar{4}$·937	422		·410	·00185	$\bar{4}$·880	541
	·405	·00245	$\bar{4}$·997	408		·420	·00186	$\bar{4}$·893	538
	·440	·00257	$\bar{3}$·053	389		·470	·00208	$\bar{4}$·990	481
	·500	·00273	$\bar{3}$·137	366		·515	·00225	$\bar{3}$·064	444
	·510	·00275	$\bar{3}$·146	364		·545	·00232	$\bar{3}$·100	431
	·540	·00285	$\bar{3}$·188	351		·570	·00241	$\bar{3}$·138	415
	·550	·00295	$\bar{3}$·210	339		·580	·00250	$\bar{3}$·161	400
	·565	·00302	$\bar{3}$·233	331		·590	·00255	$\bar{3}$·179	392
	·610	·00335	$\bar{3}$·310	299		·600	·00265	$\bar{3}$·201	377
	·640	·00370	$\bar{3}$·375	270		·635	·00292	$\bar{3}$·267	342
						·690	·00360	$\bar{3}$·394	279
			5 per cent. solution.						
e	0·400	0·00310	$\bar{3}$·093	323	*g*	0·360	0·00225	$\bar{4}$·908	444
	·450	·00322	$\bar{3}$·161	311		·510	·00274	$\bar{3}$·146	365
	·465	·00332	$\bar{3}$·188	301		·560	·00287	$\bar{3}$·207	348
	·505	·00348	$\bar{3}$·246	287		·605	·00306	$\bar{3}$·267	327
							12 per cent. solution.		
f	0·360	0·00247	$\bar{4}$·949	405	*h*	0·200	0·00258	$\bar{4}$·713	388
	·375	·00254	$\bar{4}$·979	394		·270	·00270	$\bar{4}$·863	370
	·420	·00261	$\bar{3}$·041	383		·345	·00280	$\bar{4}$·985	357
	·450	·00275	$\bar{3}$·093	364		·385	·00285	$\bar{3}$·041	351
	·470	·00280	$\bar{3}$·121	357		·420	·00290	$\bar{3}$·086	345
	·520	·00291	$\bar{3}$·179	344		·470	·00305	$\bar{3}$·155	328
	·530	·00293	$\bar{3}$·190	341		·490	·00313	$\bar{3}$·185	319
	·600	·00345	$\bar{3}$·316	290		·550	·00344	$\bar{3}$·276	291
						·570	·00370	$\bar{3}$·324	270

depression of sensitiveness of the sweet receptors. The exact concentration of the sugar solution used for this curve was not recorded, but it is certain that it was much less than 20 per cent.; it is estimated to have been about 12 per cent. Other readings obtained with this solution are not given here on account of the uncertainty of concentration. They all, however, indicated depression of the remaining sensations.

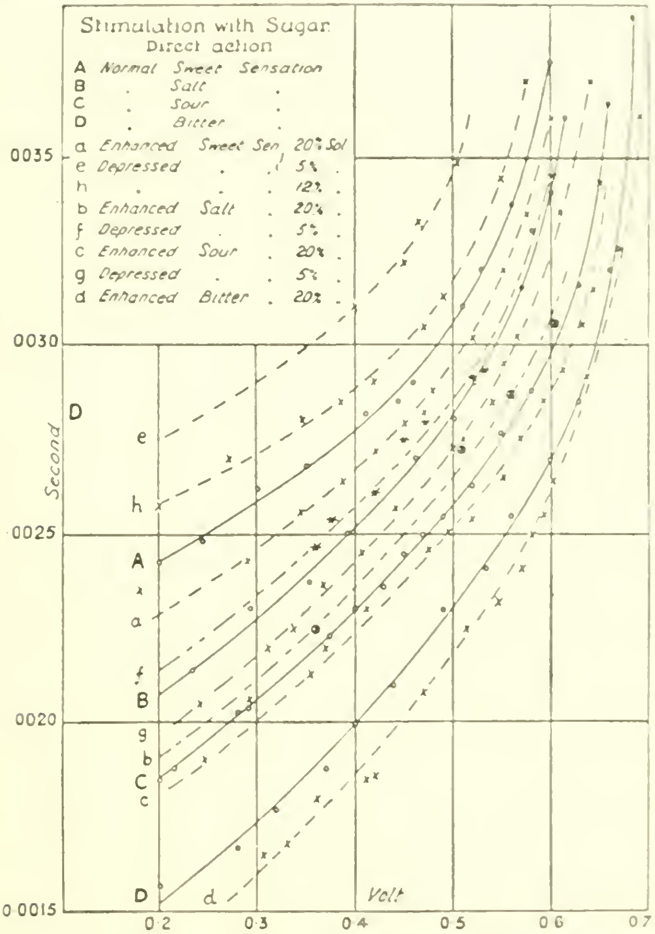

FIG. 9.—Direct action of sweet stimulus.

It was inferred that if the concentration of the solution were made still less, depression of the sensations would replace enhancement. Accordingly a series of curves was obtained after stimulation with a 5 per cent. solution of sugar. The curves *e*, *f*, *g* obtained show depression of the sensations. Curve *e* indicates a high degree of depression of the sweet sensation. Though the curve has been drawn its full course, yet it is to be noted that readings fall only on the upper half. The explanation of this probably is that the depression of the receptors was so great that the threshold of stimulation was raised to such a degree that it required twice the normal intensity of potential to arouse a perceptible sensation. Curves *f* and *g* for the salt and sour sensations show slight depression, and also raised threshold values, as indicated by the position of the lowest point on each.

These results lead to the important conclusion that the effect of a stimulus upon the gustatory receptors depends upon its concentration, low concentration causing depression of sensitiveness in excess of enhancement, and high enhancement in excess of depression.

These results are intimately connected with the interpretation of the straight line graphs shown in fig. 3. Each graph consists of three portions, as in vision and touch, corresponding to intensities of stimulation which may be distinguished as low, medium, and high. When the concentration of the solutions corresponded to the low intensities, depression of sensitiveness of the receptors resulted. When the concentration was of medium intensity, the result was enhancement of the receptors. With concentrations of high intensities, probably combinations of these two actions on the four receptors would be obtained, enhancing some and depressing the rest, as was obtained with other stimuli.

With concentrations corresponding to the intensities at which changes of slope in the graphs (fig. 3) occur, there would probably be neither enhancing nor depressing effects upon the four receptors.

Evidently further research on the effects of graded series of concentrations is needed for the complete analysis of this subject. The writers venture to express the hope that other investigators may become interested in the application of this method, and greatly extend as well as confirm or correct the general results we have herein set forth.

The nature of the processes involved in the sensory apparatus is much elucidated by the experiments now to be described.

The left side of the tongue was stimulated with the 1½ per cent. solution of acetic acid in the usual manner, and the measurements were made, as before, on the right side of the tongue, the electrodes being placed exactly on the same spot as before. The readings are given in Table VII., and the corresponding graphs are shown in fig. 10. The reflex curves, *a*, *b*, and *c*, are below the corresponding normals, indicating reflex enhancement of the sweet, salt, and sour receptors. The very short curve *d* indicates that the bitter sensation was also enhanced. There is, however, a complete absence of readings for the lower voltages, for which the writers have no explanation.

Similar curves were obtained by stimulating the left side of the tongue with a 20 per cent. solution of sodium chloride. They are plotted in fig. 11 from the readings in Table VIII. In nearly every respect they are like those obtained with acetic acid, since each of the reflex curves *a*, *b*, *c*, and *d* lies below the normal, indicating reflex enhancement of sensitiveness. It will be noted, however, that in this case there are no readings in the central part of curve *d* for bitter.

With stimulation by these two substances, acetic acid and sodium chloride, enhancement of all four gustatory sensations is produced by sensory reflex action.

These results correspond exactly with similar phenomena found in vision (1), for when one eye was stimulated with bright light, the three primary sensations, red, green, and violet, in the other were enhanced in sensitiveness. When one side of a retina was similarly stimulated, enhancement of the three sensations in the other side also resulted. These effects are readily explained as the result of sensory reflex action.

TABLE VII. REFLEX ACTION WITH 1·5 PER CENT. SOLUTION OF ACETIC ACID

	Volt V.	Duration D—Sec.	Log Q = Log VD.	I.D.		Volt V.	Duration D—Sec.	Log Q = Log VD.	I.D.
a	0·200	0·00225	$\bar{1}$·653	444	*c*	0·305	0·00202	$\bar{4}$·790	495
	·350	·00254	$\bar{4}$·949	394		·415	·00223	$\bar{4}$·966	448
	·410	·00265	$\bar{3}$·037	377		·490	·00250	$\bar{3}$·090	400
	·435	·00277	$\bar{3}$·083	361		·525	·00260	$\bar{3}$·137	385
	·490	·00288	$\bar{3}$·149	347		·580	·00275	$\bar{3}$·204	364
	·540	·00308	$\bar{3}$·220	325		·620	·00300	$\bar{3}$·270	335
	·570	·00330	$\bar{3}$·274	303		·660	·00330	$\bar{3}$·328	303
	·580	·00355	$\bar{3}$·314	282					
b	0·215	0·00198	$\bar{1}$·629	505	*d*	0·640	0·00285	$\bar{3}$·260	385
	·420	·00240	$\bar{3}$·004	417		·660	·00308	$\bar{3}$·308	325
	·495	·00269	$\bar{3}$·124	372					
	·540	·00285	$\bar{3}$·188	351					
	·580	·00305	$\bar{3}$·248	328					
	·585	·00311	$\bar{3}$·260	322					
	·600	·00324	$\bar{3}$·288	309					
	·615	·00329	$\bar{3}$·305	304					

In the sense of touch also (3) it was found that stimulation of one finger caused enhancement of the tactile sensations in another in precisely the same manner.

In all three senses, therefore, we find the same phenomena occurring, and there can be no doubt that the mode of transference of the action of the stimulus, as well as its transformation into an enhancing effect, must be due to the same cause in each, namely, sensory reflex action.

The last experiments now to be described are, however, altogether different in their result. When the left side of the tongue was stimulated with the $\frac{1}{8}$ per cent. solution of quinine bisulphate, the graphs shown in fig. 12 were obtained from observations on the right side of the tongue. The measurements are given in Table IX. In this figure curves *a*, *b*, *c*, and *d* are elevated above the corresponding normals, showing that the reflex action in this case did not cause the customary enhancement, but depression of sensitiveness of all four sensations.

In light, a similar phenomenon has long been known as the Fechner Paradox. When a piece of white paper has been fixated by one eye, the other being blindfolded, a feeble light introduced into the latter causes the white paper to appear darker. So in the sense of taste, a feeble bitter stimulus on one side of the tongue causes the sensations on the other side to become less responsive. This is, therefore, the gustatory equivalent of the Fechner Paradox.

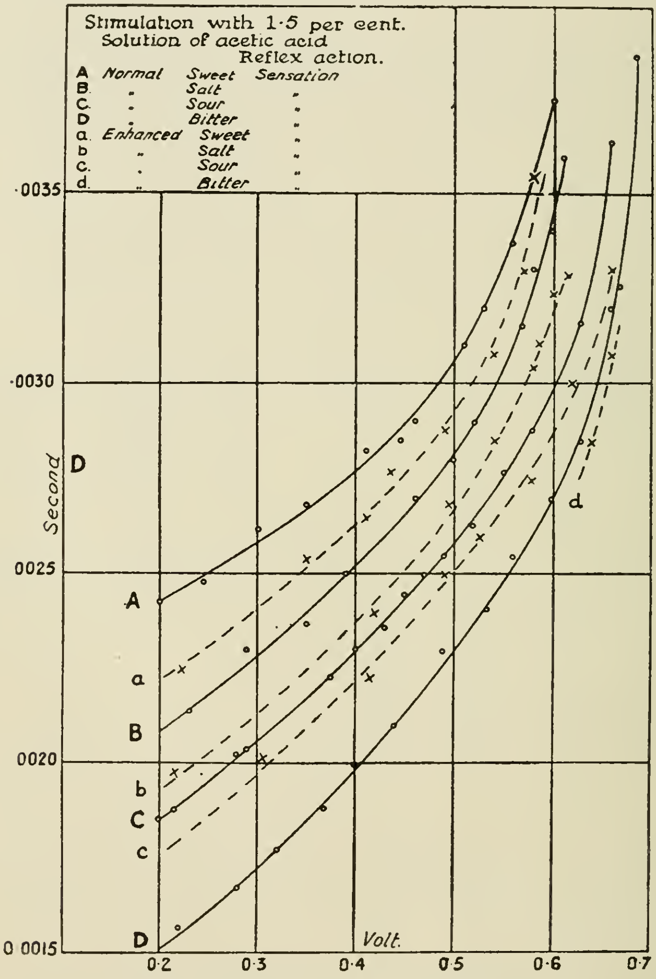

Fig. 10.—Reflex action of sour stimulus.

While these experiments were in progress, an investigation, conducted by one of the writers (Allen) into the effects of colours of varying intensity upon the colour sensations, disclosed the fact that colours corresponding in intensity to the lowest branch of the curve for vision, in fig. 4, depressed the three primary sensations, whether stimulation was in the same eye as was used for measurement, or in the other. When, however, the colours were of medium intensities corresponding to the second branch of the curve, the opposite effect—enhancement—was produced in all the sensations.

These investigations, to be published shortly, lead to the conclusion that depressory effects upon the receptor end-organs are also transferred by reflex action in a thoroughly systematic manner. Since reflex action causes opposite effects, the complete theory must embrace both. The conclusion follows that stimulation of a sensory end-organ, in addition to the excitation of a sensation in the central organs, causes the simultaneous production or release of two sets of efferent nerve impulses, one causing depression and the other enhancement of the sensory receptors. When the stimulus is weak, depression exceeds enhancement; when strong, enhancement exceeds depression. From the experiments in light just referred to, as well as from the graphs in figs. 7, 8, and 9, the effects under varying strengths of stimulation may be a little more

Table VIII.—Reflex Action with 20 per cent. Solution of Sodium Chloride.

	Volt V.	Duration D—Sec.	Log Q = Log VD.	1/D.		Volt V.	Duration D—Sec.	Log Q = Log VD.	1/D.
a	0·260	0·00238	$\bar{4}$·792	420	*c*	0·310	0·00204	$\bar{4}$·801	490
	·305	·00242	$\bar{4}$·868	413		·380	·00215	$\bar{4}$·913	465
	·420	·00270	$\bar{3}$·053	370		·470	·00239	$\bar{3}$·049	418
	·430	·00273	$\bar{3}$·068	366		·500	·00250	$\bar{3}$·097	400
	·450	·00275	$\bar{3}$·093	364		·510	·00253	$\bar{3}$·111	395
	·460	·00280	$\bar{3}$·111	357		·540	·00260	$\bar{3}$·146	385
	·475	·00282	$\bar{3}$·127	355		·580	·00280	$\bar{3}$·210	357
	·500	·00295	$\bar{3}$·170	339		·615	·00295	$\bar{3}$·258	339
	·560	·00320	$\bar{3}$·253	313		·640	·00312	$\bar{3}$·301	321
	·580	·00338	$\bar{3}$·292	296		·650	·00325	$\bar{3}$·324	308
	·590	·00355	$\bar{3}$·322	282					
b	0·190	0·00197	$\bar{4}$·573	508	*d*	0·270	0·00150	$\bar{4}$·607	667
	·230	·00201	$\bar{4}$·665	498		·360	·00179	$\bar{4}$·809	559
	·240	·00203	$\bar{4}$·688	493		·610	·00258	$\bar{3}$·196	388
	·300	·00215	$\bar{4}$·810	465		·665	·00297	$\bar{3}$·297	337
	·310	·00218	$\bar{4}$·830	459		·680	·00310	$\bar{3}$·324	323
	·360	·00230	$\bar{4}$·918	435					
	·420	·00243	$\bar{3}$·009	412					
	·465	·00254	$\bar{3}$·072	394					
	·520	·00268	$\bar{3}$·143	373					
	·635	·00338	$\bar{3}$·332	296					
	·650	·00400	$\bar{3}$·415	250					

complicated. For it has been found also that one or more sensations may be depressed and the complementary remainder enhanced by the stimulus. It will also follow that when the stimulus is of an intensity corresponding to a point where the change in slope of the curves (fig. 3) occurs, neither depression nor enhancement of the sensations should occur; that is, the two reflex effects counterbalance. This is indicated in the curves for sugar (fig. 9), and has also been found in vision. These phenomena indicate very clearly that the state and phenomena of reciprocal innervation that Sherrington has so elegantly demonstrated in muscular movements are also to be found underlying all sensory actions.

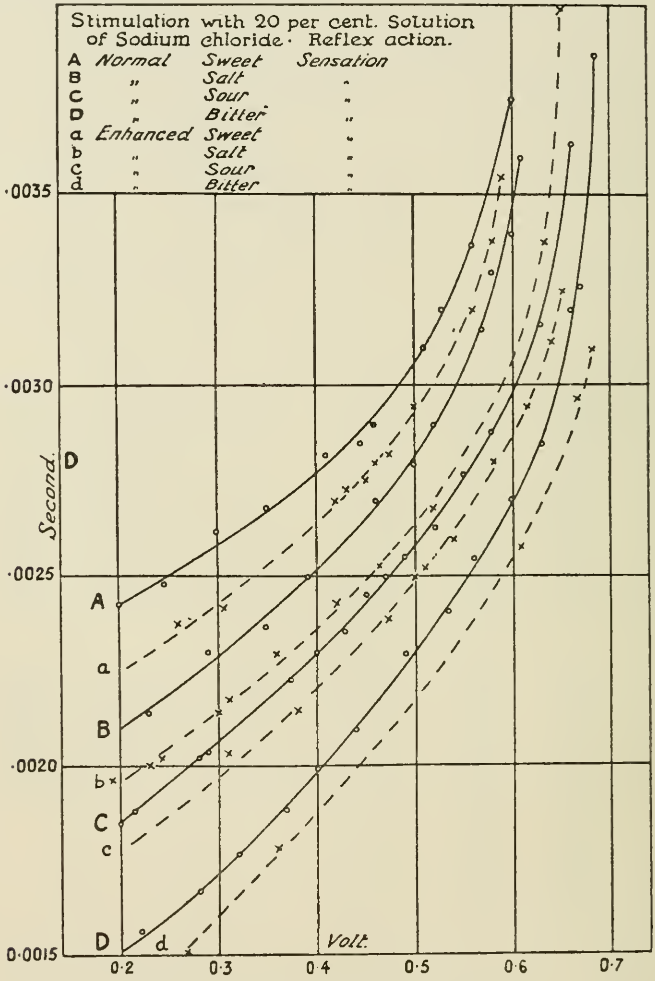

Fig. 11.—Reflex action of salt stimulus.

The equations representing the various sensory actions are now seen to possess some significant uniformities:

$$\frac{1}{D} = k \log I + C \quad \text{(Vision)}$$

$$\frac{1}{D} = -k \log Q + C \quad \text{(Taste)}$$

$$D = k \log P + C \quad \text{(Audition)}$$

$$D = -k \log P + C \quad \text{(Touch)}$$

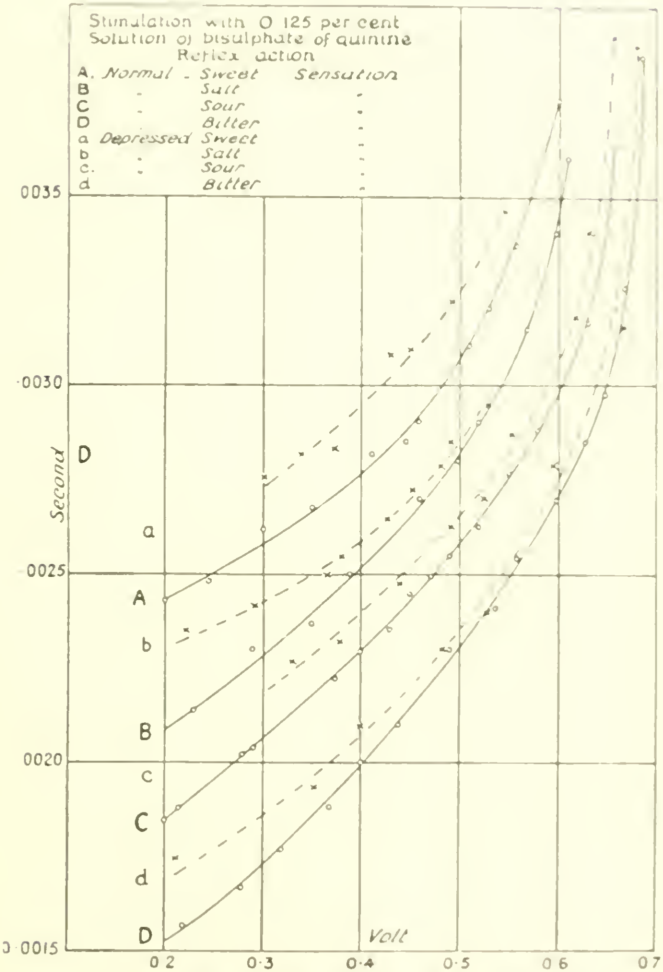

Fig. 12.—Reflex action of bitter stimulus.

In the first two, involving the reciprocal, $\frac{1}{D}$, of the time of the persistence of the effect of stimulation at its critical frequency, low intensities caused depression to exceed enhancement, and higher the reverse.

In the last two equations, where D appears directly, low intensities of stimulation cause enhancement to exceed depression, and higher the reverse. This has been proved experimentally for all senses, except for low intensities in audition. The difference in form of the left-hand members of the two pairs of equations is evidently determined by similarities and differences in the nerve actions.

The positive and negative signs have a mathematical significance in reference to the slope of the graphs and their axial intercepts ; but we do not at present see their physiological meaning.

It may be recorded here that an attempt was made in this laboratory to reduce the sense of smell to measurement by the same electrical method described in this paper. An undoubted effect was obtained by placing long electrodes in the nostrils, but the intermittent current evoked sneezing to such an extent that not a single measurement could be obtained. It is quite possible that some other investigator may be successful in devising a method to overcome this difficulty.

TABLE IX.—REFLEX ACTION WITH 0·125 PER CENT. SOLUTION OF QUININE BISULPHATE.

	Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.		Volt V.	Duration D—Sec.	Log Q= Log VD.	1/D.
a	0·300	0·00276	$\bar{4}$·918	362	*c*	0·330	0·00227	$\bar{4}$·874	441
	·340	·00282	$\bar{4}$·982	355		·380	·00232	$\bar{4}$·945	431
	·375	·00283	$\bar{3}$·025	353		·440	·00248	$\bar{3}$·037	403
	·430	·00308	$\bar{3}$·121	325		·490	·00263	$\bar{3}$·104	380
	·450	·00310	$\bar{3}$·146	323		·525	·00270	$\bar{3}$·152	370
	·495	·00322	$\bar{3}$·201	311		·555	·00287	$\bar{3}$·201	348
	·545	·00346	$\bar{3}$·276	289		·595	·00302	$\bar{3}$·255	331
						·620	·00318	$\bar{3}$·294	314
						·630	·00340	$\bar{3}$·330	294
						·655	·00392	$\bar{3}$·410	255
b	0·220	0·00235	$\bar{4}$·713	426	*d*	0·210	0·00175	$\bar{4}$·566	571
	·290	·00242	$\bar{4}$·846	413		·355	·00194	$\bar{4}$·838	515
	·365	·00250	$\bar{4}$·960	400		·400	·00210	$\bar{4}$·924	476
	·380	·00255	$\bar{4}$·986	392		·485	·00230	$\bar{3}$·049	435
	·425	·00265	$\bar{3}$·053	377		·530	·00240	$\bar{3}$·104	417
	·450	·00273	$\bar{3}$·090	366		·615	·00279	$\bar{3}$·236	358
	·480	·00279	$\bar{3}$·127	358		·665	·00315	$\bar{3}$·320	317
	·490	·00285	$\bar{3}$·146	351		·680	·00390	$\bar{3}$·423	256
	·530	·00295	$\bar{3}$·193	339					

ZWAARDEMAKER (7) is of the opinion that there are nine fundamental olfactory sensations. If this be the case, then the experimental results by this method should prove even more complicated than those obtained in taste. It is therefore all the more desirable that a suitable method for the analysis of the olfactory sensations should be devised.

In figs. 13, 14, 15, and 16 are shown the normal curves for each of the taste sensations, sweet, salt, sour, and bitter respectively, together with similar graphs for the enhancement and depression of each sensation, all reduced to logarithmic form. In each figure the middle graph is the normal, the highest is that for enhancement, and the lowest for depression. The graphs for each of these are selected from the preceding figures, their origin being clearly indicated in the upper part of each diagram. These also identify the values in the various tables from which they are plotted. Most of the graphs in the figures have the three branches in a marked degree; others do not show the uppermost branch because of insufficient readings. There can be no doubt, however, that when fully and correctly developed, all graphs have the third branch.

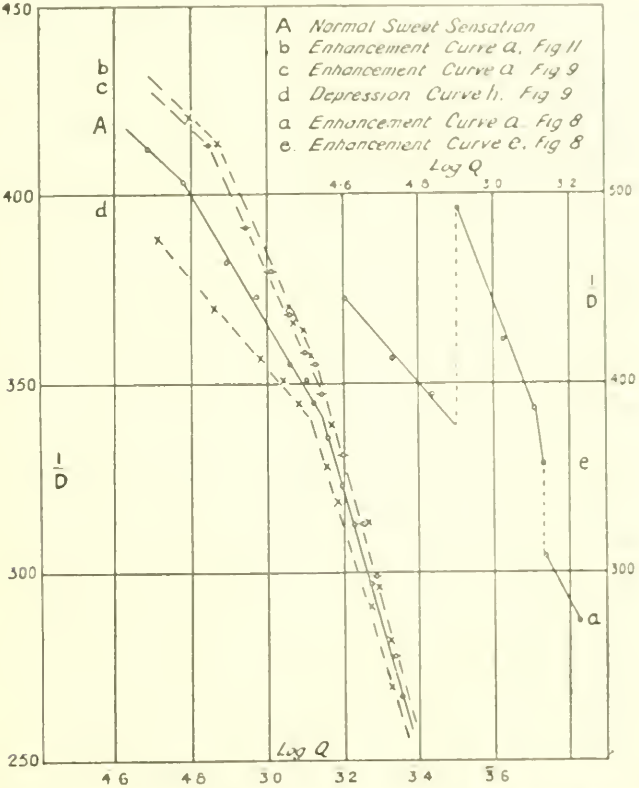

Fig. 13.—Normal, enhancement and depression graphs for the sweet sensation. Curves are from the figures indicated, reduced to logarithmic form. Curves *a* and *e* show anomalous enhancement of the sweet sensation in fig. 8.

These figures prove that the curves obtained after the direct and reflex actions of the various stimuli employed have had time to produce their characteristic effects upon the gustatory receptors, likewise conform to the same mathematical law as the normals. Their convergence indicates also that the two constants in the equation have values differing from the normal in each of the three branches. This is to be expected, since the action of any stimulus cannot destroy or alter the character of the response of the receptors, but only the magnitude.

The convergence of the graphs to a point at high intensities is very striking, and perhaps indicates that after meeting they would combine into one with a further change of slope.

In discussing the direct action of sodium chloride, a striking peculiarity in its enhancing action upon the sweet receptors was shown in fig. 8. In fig. 13, the two enhancement curves from the former figure are drawn in logarithmic form to a somewhat different vertical scale, and displaced to the right to avoid interference with the main diagram. The vertical dotted lines clearly indicate that curve *e* fits into the vacant part of curve *a*. Both are enhancement curves ; but for some reason the enhancing action of sodium chloride has caused an extraordinary degree of sensitiveness of the sweet receptors to stimuli corresponding in intensity to the middle portion of curve *a*.

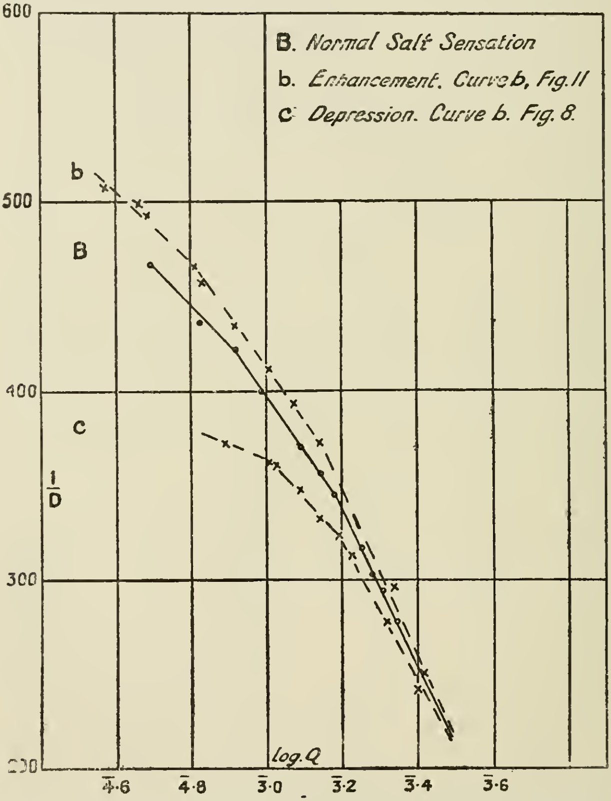

Fig. 14.—Normal, enhancement and depression graphs for the salt sensation. Curves are from the figures indicated, reduced to logarithmic form.

The legitimacy of the method of electrical stimulation of the sensations of taste by means of electrolysis of the saliva is so fully established by all the experimental results which have now been set forth, that no further argument appears to be necessary.

The question, however, arises whether there is only one type of end organ which is responsive to all taste stimuli, the different sensations being due to different degrees of stimulation; or whether there are present in the tongue four independent or partially independent gustatory end-organs, each sensitive specifically to one definite primary taste. Only one argument appears to favour the former view, namely, that no person has yet been found insensible to one or more of the primary tastes. Such a gustatory condition would be analogous to colour-blindness in vision. The latter view is supported by all the experimental evidence here presented, as well as by the phenomena previously observed through other methods.

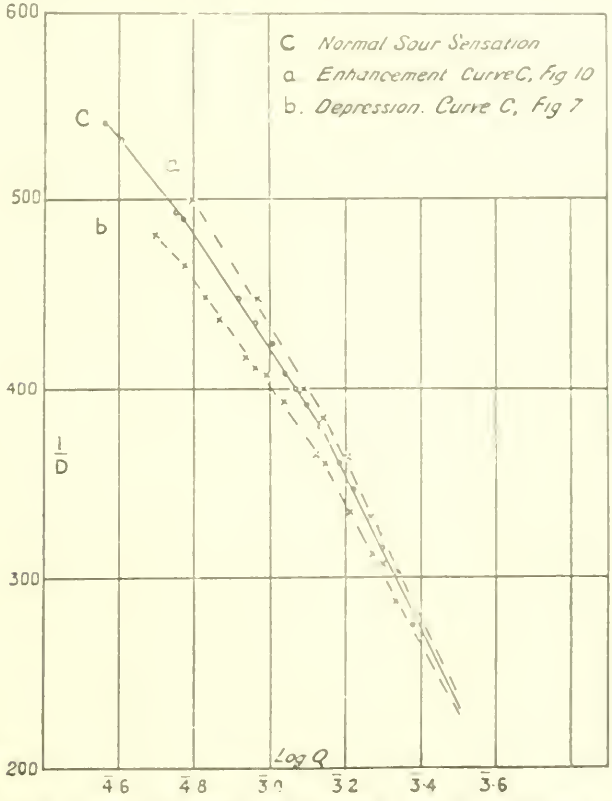

Fig. 15.—Normal, enhancement and depression graphs for the sour sensation. Curves are from the figures indicated, reduced to logarithmic form.

There are many striking resemblances between visual and gustatory sensations. Perhaps the most obvious and prominent is that each sense is characterised by a limited number of definite sensations, three in vision and four in taste. Though partially independent of each other, they are, however, bound together by both the afferent and efferent nerve systems to such an extent that every adequate stimulus acts and reacts on each, thereby making every perception of colour or taste a composite result, in which one or more single factors predominate over the remainder.

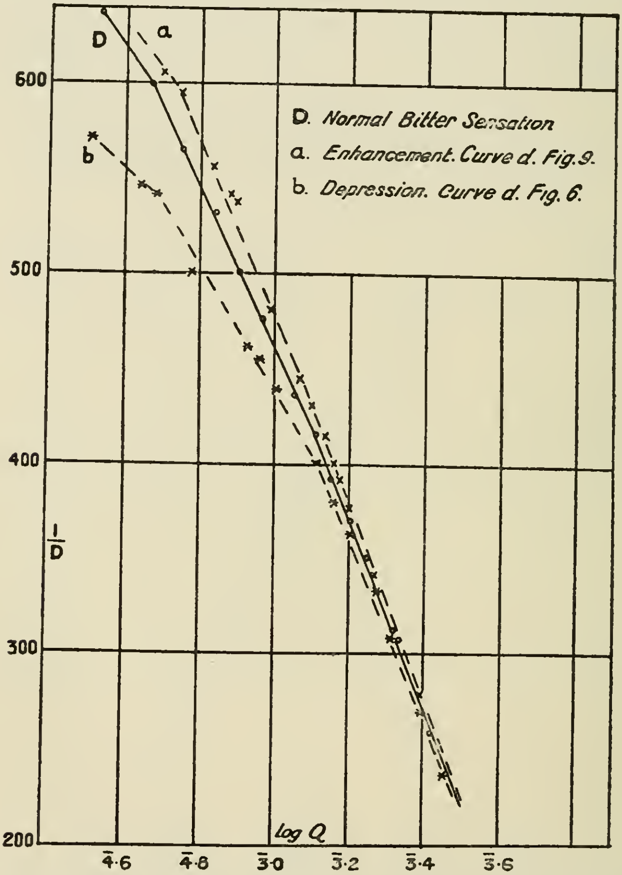

Fig. 16.—Normal, enhancement and depression graphs for the bitter sensation. Curves are from the figures indicated, reduced to logarithmic form.

In consequence of these mutual interactions, colour and gustatory sensations are never saturated, and in each sense an almost infinite number of combinations become possible. This gives in the one case an extraordinary richness in the variety of colour effects which are presented in nature and in art, and in the other an equal wealth of gustatory experiences, which, though not regarded on as high an artistic level as the former, and peculiarly susceptible of great abuse and debasement, contribute immensely to the enjoyment of life, and deservedly are recognised among the refinements of civilisation.

The analogy between complementary tastes and complementary colours, as well as between simultaneous and successive contrast in the two senses, is well known, and has been referred to at the beginning of this paper.

The subjective phenomena of vision, such as negative after images and the self-light of the retina, may possibly have analogies in taste. Should this be the case, a single taste stimulus might be expected to be followed by a negative after-image consisting of a complementary taste produced without any stimulus, but arising from the continuance of efferent nerve discharges. Quite possibly, also, some sensations of taste, perceived under peculiar conditions, but without external stimulation, may be analogous to the self-light of the retina, which one of the writers has indicated (6) to be probably of reflex origin.

Adequate stimulation of the gustatory sensations usually occurs simply by placing materials upon the tongue. With some substances, especially those that are not readily dissolved, a more intimate contact with the gustatory receptors must be obtained by a simple mechanical device. This is provided by pressing the substance with the tongue against the ridges on the roof of the mouth, which prevent it from slipping over the otherwise smooth lubricated surface. By this means the tongue may be rubbed over the stationary material, forcing it into the closest possible contact. With smooth artificial plates this action is greatly lessened, which sometimes interferes with taste perceptions. A plate, therefore, should have reproduced upon its surface every feature that characterises the portion of the roof of the mouth which it covers.

The sensory interactions described in this paper are, no doubt, the unconscious basis of a well-ordered menu, as well as of the approved seasoning of various articles of food. The sharp taste contrasts commonly used enhance the momentarily depressed sensations, rendering the perceptions of various flavours more vivid, just as an artist employs contrasting colours to heighten the effect of a colour scheme. Such considerations as these may be of some practical service in the science of dietetics, not only in normal life, but also in the various pathological conditions in which a proper and inviting diet is at once of great importance and difficult to arrange.

The development of experimental psychology has been excessively hampered by the impossibility of devising definite units of sensation. This investigation may possibly remove that disability in some degree, not indeed by providing units, but by demonstrating that under certain conditions sensations are accurately associated with, or proportional to, time measurements. To the extent therefore in which sensory phenomena can be associated with intervals of time, psychology may be placed on the basis of exact measurement.

This investigation is one of a series of researches relating to colour vision and other sensory actions now being conducted under the direction of Professor FRANK ALLEN, with the financial assistance of the Research Council of Canada, to which body we desire to express our thanks.

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15*th June* 1924.

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The Persistence of Vision

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The Persistence of Vision

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THE frequent occurrence of phenomena which depend for their explanation upon the principle of the persistence of vision was the evident reason why this part of physiological optics received very early attention. The peculiar appearance of rapidly rotating bodies, such as the apparent smoothness which rough surfaces assume, the transparency of wheels, the periodic visibility of the limbs of animals in swift motion, have been noticed by observers in ancient times, and in some cases correctly accounted for by the fact that the sensation continues for some time after the exciting cause ceases to act.

It can scarcely be doubted that people in the earliest ages have seen the circle of light produced by revolving a burning coal on the end of a stick; yet the first record of this observation is in the fifth century of our era.

According to Plateau*, to whose history of this subject we are greatly indebted, the writings of Aristotle (384—322 B. C.) contain the first known references to the persistence of vision. In his treatise *On Dreams*, Aristotle, in illustrating their origin, mentions the effect obtained when looking at a dark object after glancing at the sun. "The result is", he says, "that one sees nothing owing to the fact that the sense-process stimulated by the light, still lurks in the eyes. And if one looks a long time at a single color, whether it be white or green, things appear to be similarly colored wheresoever we turn our eyes. Again if we look at the sun and then shut our eyes there appears first of all a color like the actual one, which then changes to scarlet, then to purple, until it passes into blackness and vanishes."

*Memoir, published in 1877 by the *Belgian Academy of Sciences*.

Aristotle also refers to the illusion of motion produced by directing the attention to objects at rest after looking for some time at a swiftly flowing stream of water.

These illustrations of the continuance of impressions in the organ of vision are used by the Greek philosopher, not to found a science of physiological optics, but to afford an explanation of dreams, which accordingly are considered to be the persisting images or after motions of sensations. For some of the sense impressions occurring during our waking state are forced into the background by the exercise of the intellect. But when the latter is quiet in sleep and the judgment and will are powerless to interfere, the neglected but persisting sensations come to consciousness in dreams.

Three centuries later the poet Lucretius (95 – 51 B. C.) endeavored to account for dreams in a far different and more materialistic manner, but yet one involving somewhat the same idea. For this purpose he makes use of the theory of vision of Epicurus which he develops in great detail. All bodies have certain properties by virtue of which images (*simulacra*), like delicate films, are constantly being pealed off from their surfaces and projected away with great velocity. These images are characterised by extreme fineness of texture and are of varying degrees of thinness. They never lose their identity, form, and color. In their aimless journeyings it is possible for two images to coalesce into one. "For assuredly," says Lucretius, "no image of a centaur is formed out of a live one, since no such living creature ever existed; but when images of a horse and a man by chance come together they readily adhere at once on account of their fine nature and thin texture."

Usually these images excite vision by entering the eyes in a constant stream. But during sleep images possessing an extraordinary degree of thinness enter through the pores of the body and impress the mind within, so causing dreams. Furthermore, "it is not strange that images move and throw about their arms and limbs in regular measure: for sometimes in sleep an image is seen to do this. When the first has gone and a second has been born in another posture, the former one seems to have altered its attitude. This, remember, you must assume to take place with exceeding celerity."

In this passage Lucretius, amidst all his fantastic errors, has enunciated the principle of the motion pictures which have been brought to such a state of perfection.

The difficulty of explaining the formation of the rainbow, in early times occasioned many theories of light and color, which, though full of absurdities, nevertheless display the unfailing resourcefulness of the philosophic mind. Not the least ingenious was that of Seneca (4 B. C. – 65 A. D.), the tutor and apologist of Nero. According to him the rainbow is due to the image of the sun reflected by each of the falling raindrops. These innumerable images are not intermittent but are combined by the eye into one continuous but elongated effect. The colors were supposed to be produced in some inexplicable fashion by the combination of the sun and its image.

In the second century of our era, Ptolemy records the observation that if a disk is painted with different colors and rotated with sufficient velocity, the separate colors can no longer be distinguished but are blended into a single tint which results from the mixture. If the colors are at different distances from the center, each gives the appearance of a circle of the same color. To the same cause, in the opinion of Ptolemy, on account of the rapidity of their flight, meteors owe the appearance of long luminous trains.

Ptolemy also mentions the occurrence of positive after-images under such conditions as were stated by Aristotle.

The first recorded observation of the luminous curve traced by a burning body moving rapidly in the dark is that of Boethius (455—525 A. D.) at the end of the fifth century.

This has a peculiar interest as it served Segner and D'Arcy more than a thousand years later as a means of measuring the duration of the sensation of light upon the eye.

An explanation of this phenomenon was attempted by the Arabian physician and philosopher, Avicenna or Ebn Sina, (980—1037), "the most extraordinary man that the nation produced." The appearance of the revolving fire-brand is due to the arrival at the common sensorium of a series of images which, owing to their rapid succession, are not judged with sufficient rapidity to be separately distinguished, and in consequence they appear altogether circularly arranged.

Another explanation of the persistence of vision was given a little later by Alhazen (d. 1038). In his opinion the seat of vision was the crystalline lens, which exercised at once the functions of a transparent and of a sentient body. Light and colors made it undergo certain modifications which resulted in sensation. The continuance of these modifications for a short time after their cause ceased to act gave rise to the peculiar phenomena of the persistence of vision. To Alhazen is due the colored top which offered a simpler method of mixing colors than the disk of Ptolemy.

In the thirteenth century Albert le Grand remarked that the apparent straight lines traced by falling raindrops were due to the persistence of vision.

Father D'Aguillon (1567—1617) seems to have held much clearer views than his predecessors respecting visual impressions. According to him images do not persist in the eye after the disappearance of the objects which produce them; for images necessarily vanish with their causes; that which endures for some time is a certain alteration which the organ of vision has suffered from the action of light. In connection with his views he concludes that Aristotle was deceived in attributing dreams to the mere continuance of visual impressions. D'Aguillon also remarked that bodies, such as bullets, moving with great velocity fail to make any impression on the eye; and also that bodies that are moving at such a speed as to be only indistinctly visible appear to occupy at one time all the space they describe.

A retrograde step was made by Michaelius (1645), who attempted to show that visual images are not continued in any of the parts of the eye, but only in the imagination. After looking at a window for some time the eyes are closed to watch the image closely. A sudden pressure is exerted on the eyes by the fingers which causes a bright scintillating light which envelopes the whole retina. If the image were on the retina this light ought not to be perceived at all, or the impression should be slightly enfeebled. The observed reappearance of the image after it had ceased for a moment to be visible was attributed to a conflict between the imagination and the judgment in which they were alternately victorious. "The former sees in its turn what the latter declares to have no existence."

Among his observations on colors, Robert Boyle, "the father of chemistry and the uncle of the Earl of Cork", cites as an extreme illustration of the persistence of vision the case of a man who, without protecting his eyes, looked at the sun through a telescope. At the time Boyle wrote (1663) the image of the sun had persisted for ten years.

In 1667 Father Fabri stated his opinion that the visual effect produced by a burning coal in rapid motion is due to the impression which is caused at the back of the eye by the luminous object lasting for some time. Plateau considers this to be the first time that anyone has clearly attributed an effect of this kind to the persistence of visual impressions.

Father Deschales (1674) attacked the views of Alhazen and D'Aguillon, and substituted for their obscure explanations the principle of the persistence of vision. In support of this principle he cites several illustrations. In the game which children play a coin is pressed for some moments against the forehead and then removed without the person being aware of it. The sensation persists so vividly that the child will make all sorts of grimaces to cause the imaginary coin to fall.

In an analogous manner persons who have looked for some time at an eclipse of the sun with unprotected eyes, have seen continually before them for a month a yellowish image of the sun.

Deschales also cites in this connection the succession of after images seen after viewing a brilliant red color for some time. He further remarks that the persistence of vision also explains why a very rough body in rapid rotation appears uniformly smooth.

In 1685 Zahn was unfortunate enough to observe directly an eclipse of the sun. The image persisted for a month, during which time he saw apparently on every object he looked at, a large spot the middle of which was black and the outside yellow.

A little later Mariotte carried the continuance of visual impressions to the extent of making it the chief cause why objects and their colors cannot be perceived for some time after passing from the light into a darkened room.

In a letter to the philosopher Locke in 1691 Sir Isaac Newton wrote:—"The observation you mention in Mr. Boyle's book of colours, I once made upon myself with the hazard of my eyes. The manner was this: I looked a very little while upon the sun in the looking-glass with my right eye, and then turned my eyes into a dark corner of my chamber, and winked, to observe the impression made, and the circles of colours which encompassed it, and how they decayed by degrees, and at last vanished. This I repeated a second and a third time. At the third time when the phantasm of light and colours about it were almost vanished, intending my fancy upon them to see their last appearance, I found to my amazement, that they began to return, and by little and little to become as lively and vivid as when I had newly looked upon the sun. But when I ceased to intend my fancy upon them, they vanished again. After this, I found that as often as I went into the dark, and intended my mind upon them, as when a man looks earnestly to see anything which is difficult to be seen, I could make the phantasm return without looking any more upon the sun; and the oftener I made it return the more easily I could make it return again. And at length, by repeating this without looking any more upon the sun, I made such an impression upon my eye, that if I looked upon the clouds, or a book, or any bright object, I saw upon it a round bright spot of light like the sun: and, which is still stranger, though I looked upon the sun with my right eye only, and not with my left, yet my fancy began to make the impression upon my left eye as well as upon my right. For if I shut my right eye and looked with my left, the spectrum of the sun did not appear till I intended my fancy upon it, and by repeating, this appeared every time more easily. And now in a few hours time, I had brought my eye to such a pass, that I could look upon no bright object with either eye, but I saw the sun before me: but to recover the use of my eyes, I shut myself up in my chamber made dark, for three days together, and used all means to divert my imagination from the sun. For if I thought upon him, I presently saw his picture, though I was in the dark. But by keeping in the dark, and employing my mind about other things, I began in three or four days to have some use for my eyes again; and by forbearing a few days longer to look upon bright objects, recovered them pretty well, though not so well, but that for some months after the spectrum of the sun began to return as often as I began to meditate upon the phenomenon, even though I lay in bed at midnight with my curtains drawn; but now I have been very well for many years though I am apt to think, that if I durst venture my eyes, I could still make the phantasm return by the power of my fancy * * * * And so your question about the cause of this phantasm involves another about the power of fancy, which I must confess is too hard a knot for me to untie. To place this effect in a constant motion is hard, because the sun ought then to appear perpetually. It seems rather to consist in a disposition of the sensorium to move the imagination strongly, and to be easily moved both by the imagination and by the light as often as bright objects are looked upon."

Newton also made use of the persistence of vision to enforce his proof that the recombination of the spectral colors gives white. In his *Opticks* (2nd Ed. 1718, p. 122) he described an experiment in which the colors of the spectrum fell upon a lens which brought them all into a single white spot. He then interposed in the path of the light a comb-shaped 'instrument' with sixteen teeth, each of which was over an inch wide, and with spaces between them two inches in width. When this was moved slowly the spot changed color continuously.—"But if I so much accelerated the Motion, that the Colours by reason of their quick succession could not be distinguished from one another, the appearance of the single Colours ceased. There was no red, no yellow, no green, no blue, nor purple to be seen any longer, but from a confusion of them all there arose one uniform white Colour. Of the Light which now by the mixture of all the Colours appeared white, there was no part really white. One part was red, another yellow, a third green, a fourth blue, a fifth purple, and every part retains its proper Colour till it strike the Sensorium. If the Impressions follow one another slowly, so that they may be severally perceived, there is made a distinct Sensation of all the Colours one after another in a continual succession. But if the Impressions follow one another so quickly that they cannot be severally perceived, there ariseth out of them all one common Sensation, which is neither of this Colour alone nor of that alone, but hath itself indifferently to 'em all, and this is a Sensation of Whiteness. By the quickness of the Successions the Impressions of the several Colours are confounded in the Sensorium, and out of that confusion ariseth a mix'd sensation. If a burning Coal be nimbly moved round in a Circle with Gyrations continually repeated, the whole Circle will appear like Fire; the reason of which is, that the Sensation of the Coal in the several places of that Circle remains impress'd on the Sensorium, until the Coal return again to the same place. And so in a quick consecution of the Colours the Impression of every Colour remains in the Sensorium, until a revolution of all the Colours be completed, and that first Colour return again. The Impressions therefore of all the successive Colours are at once in the Sensorium, and jointly stir up a Sensation of them all; and so it is manifest by this Experiment, that the commix'd Impressions of all the Colours do stir up and beget a Sensation of white, that is, that whiteness is compounded of all the Colours."

In "Query 16" Newton suggested how the measurement of the presistence of vision might be made: "And when a Coal of Fire moved nimbly in the circumference of a Circle, makes the whole circumference appear like a Circle of Fire: Is it not because the Motions excited in the bottom of the Eye by the Rays of Light are of a lasting nature, and continue till the Coal of Fire in going round returns to its former place? And considering the lastingness of the Motions excited in the bottom of the Eye by Light, are they not of a vibrating nature?"

A curious application of the persistence of vision combined with assumed small movements of the eyes was made by Jurin (1738) to explain the rayed appearance of stars. As the eye moves the image of the star falls successively on different points of the retina, and if the succession of images is excessively rapid the light from the star by its persistence will appear to fall simultaneously on all parts.

The same idea was used by Boerhaave (1738) to explain why we see several objects at once. According to him only one object is perceived at a time, and but one point of that distinctly. But the eye possesses the power of running from one object to another with an "incredible" velocity, which, combined with the persistence of vision, produces the illusion that all the impressions are simultaneous.

In 1740 Segner proposed to determine approximately the distance which might be supposed to separate luminous particles according to the corpuscular theory of light. Since vision persisted for a short interval of time it was not necessary to assume that the light corpuscles entered the eye in closely packed streams. Measurements were made by him to determine the time factor of persistence of vision. He concluded that when a glowing coal is given the precise velocity sufficient to complete the luminous circle, the duration of the sensation is then equal to that of one revolution of the coal. He found this interval to be about one-half of a second, but in order to be on the safe side he decided to adopt the value of one-tenth of a second. If therefore luminous particles entered the eye at these intervals of time continuous vision would result. From the known velocity of light Segner concludes that the distance between successive particles of light is about "two and a half diameters of the earth," or nearly twenty thousand miles.

Plateau remarks that this was the first time anyone attempted to measure the persistence of visual impressions.

In order to explain the persistence of images in the eye, Hamberger (1751) assumed the retina to be elastic, and therefore any impulse sets up vibrations which continue for some time after the disturbing action ceases. The sensitive mind is also affected for the same length of time as the retina which results in a continued perception of the image.

The first time anyone tried to obtain white by the rotation of a colored disk was, according to Plateau, in 1752, when

Musschenbroek divided the upper surface of a top into seven colored parts in the proportions in which the colors occur in the solor spectrum. When this was rotated he found the surface to assume the appearance of an imperfect white.

In 1765 Scopoli utilized the persistence of vision to determine or rather to define the colors of butterflies. A small wooden disk mounted on an axle was divided into eight equal sectors, a determined number of which he covered with what he called the primary colors. Upon rotation a uniform tint results which can be varied to match the desired colors. Scopoli attributes the invention to Father Poda.

In the same year the Chevalier D'Arcy undertook to measure the duration of the visual sensation, for that purpose making use of the same method as Segner, of whose work, however, he was for a long time unaware.

The apparatus of D'Arcy consisted of a series of wheels geared to each other and set in rotation by a falling weight. The most rapidly rotating wheel carried an arm upon the end of which was a glowing coal or other luminous body. The rate of rotation of the wheel could be regulated and its speed measured. The observations were made at night, the observer being placed at a distance of about fifty meters. D'Arcy concluded that the duration of an impression of light was eight "tierces" or 0.133 second. Observation of the light through a telescope or from a different distance made no measurable difference in the duration. He noticed that on opening his eyes suddenly after closing them for some time that the ring of light was momentarily broken.

D'Arcy placed on the instrument a paper disk pierced by a small hole. On looking through this at a distant object, and giving the disk a sufficiently rapid rotation the object was seen constantly but much dimmer. He also found that a white body illuminated by the sun gave the same duration of the sensation as the glowing coal. Though he did not carry out his purpose, D'Arcy proposed to ascertain whether the brightness, color, and distance made any difference in the time of the persistence of vision, and also intended having similar measurements made by other observers.

When a disk divided into sectors of two different colors is rotated rapidly, the eye perceives a uniform tint resulting from the mixture of the colors. The explanation of this phenomenon offered by Kratzenstein (1781) was as follows. Each color communicates to the nerve fibres of the retina a vibratory movement whose frequency gives us the color, just as the frequency of vibration of the auditory nerves informs us concerning the pitch of sounds. When two sounds are in accord the combination of the two produces the sensation of a single sound. The same is true of the visual nerves; and Kratzenstein further held that colors have their octaves, fifths, thirds, etc. corresponding to the same intervals of the musical scale. In support of the assumed vibratory motion of the visual nerves he cited the persistence of impressions, and also the colors through which the negative after image passes.

In a paper in the *Philosophical Transactions* of the Royal Society (1786) R. W. Darwin refers to after-images as "ocular spectra". The positive images, which are termed "direct ocular spectra," are said to depend on this principle:—"A quantity of stimulus a little greater than the natural quantity excites the retina to an action spasmodic which ceases after a small number of seconds."

In looking through a tube in which a sectored disk was rotated, Darwin remarked that objects are seen only a little less clearly than if nothing were in the tube. In commenting on the value given by D'Arcy for the duration of the "direct spectrum" caused by the revolution of a glowing coal Darwin remarked that this was to be considered as the duration of the shortest of these spectra. He makes the additional observation that in the fatigued eye the direct spectrum may last several seconds longer than in the normal, and that the duration will vary according to conditions of the experiment and of the eye among which fatigue is especially important.

In an "Essay upon single vision with two eyes," (1792), Wells remarked that the act of vision seems to embrace simultaneously a large number of objects on a wide field, although the area of distinct vision is very small. The explanation of Boerhaave, given above, that the eye rapidly turns from one object to another, the persistence of vision then giving the impression that these objects are seen simultaneously, is rejected by Wells. The grounds of his objection are that the duration of impressions upon the retina will vary according to the brightness of the images, and that the field of distinct vision will vary according to the intensity of the light; also that the persisting impressions due to one object would be carried to another and that all impressions would then be mingled in confusion in one place. He concludes that the fleeting impressions are perceived by some faculty higher than that of vision.

In 1796 Voigt experimented on tints produced by the rapid rotation of disks divided into colored sectors, the colors being carefully chosen so as to match as closely as possible those of the solar spectrum. A mixture of the seven principal colors was found to produce white. Voigt also discovered that a combination of red, green, and violet sectors, with angular sizes proportional to 100, 168, and 150, also gave white. The colors produced in these experiments with disks were not the same, he noticed, as those obtained by mixing similarly colored rays of the spectrum. This he attributed to the impurity of pigment colors; and stated also that the color of the revolving disk is a mixture only by illusion.

In 1800 Lüdicke studied color effects by using the method of disk rotation with the seven Newtonian colors. He noticed that a pure white was very difficult, if not impossible, to obtain. The analogy of the spectrum with the musical scale was also used by him. The series of hues from red to violet was compared to a uniform chromatic scale, the ratio of its intervals being $\sqrt[12]{\frac{1}{2}}$, and the angular widths of the colors in the disks were proportional to these numbers. Lüdicke mixed colors corresponding to strong acoustic dissonances, but found the resulting color so beautiful and agreeable to the eye that he concluded a marked difference between the action of colors and of sounds must exist. He also employed systems of these colors chosen so that when compared with sounds they constituted chords. Twenty-four of these were employed with the remarkable result that the resultant tint always approached white, seven of the combinations being particularly good.

In 1800 Young stated, without citing any investigation, that the duration of an impression upon the eye appeared to increase with the brightness of the light. The time interval was stated to vary from 0.01 sec. to 0.5 sec.

In 1829 Plateau made extensive investigations on the persistence of vision, or, as it is now usually termed, the critical frequency of flicker, which he published in his work: "Dissertation sur quelques propriétés des impressions produite par la lumiére sur l'organe de la vue", which was also published in German in Poggendorff's *Annalen*, Vol. 20, 1830.

He adopted in part the method of D'Arcy but improved and extended his results. Plateau remarked that in attempting to measure the absolute duration of an impression we can hope to get only approximate results, as the observed time is obviously that in which there is some perceptible intensity. The investigations on the persistence of colors were made on strips of colored papers pasted on a sector of a disk 90° in angular width. The color alternated with black velvet. The mean durations of impressions were:

White	*Yellow*	*Red*	*Blue*
0.35 sec.	0.35 sec.	0.34 sec.	0.32 sec.

D'Arcy had found that the glowing coal gave a value of 0.13 sec., and that white paper gave 0.35 sec. Plateau criticised D'Arcy's experiments but was unable to account for the difference.

Another experiment was arranged with twenty-four sectors, half of which were black and half white or colored. The black effect was improved by cutting out the alternate sectors and placing a black velvet screen behind the disk. The tint of rotation was that of a mixture of black and the particular color used. With papers of the same color as were used before Plateau now obtained duration values for uniformity of tint much smaller than before:

White	*Yellow*	*Red*	*Blue*
0.191 sec.	0.199 sec.	0.232 sec.	0.295 sec.

Plateau remarked that the sensation of blue lasts longer without decay than the others.

Helmholtz discussed this subject with great clearness and detail in his work *Physiologischen Optik*. He first distinguishes carefully the positive from the negative after-images, and then combines the former with the persistence of vision. He points out that in order to secure the effect of continuous illumination the repetition of the impression must be so rapid that the consecutive effect of each does not sensibly diminish before the next reaches its maximum.

If a disk on which light points were placed is rotated, circles of light will be formed by the persistence of impressions. Helmholtz showed that each luminous circle appears as if all the light which each of the points emits were distributed uniformly over the entire circumference of the circle. This principle applies both to monochromatic and to composite light.

If this law is applied to the action of the retina itself it may also be restated thus:—When a point of the retina is impressed by a light which undergoes periodic variations, and if the duration of the period is sufficiently short, a continuous impression is produced equal to that which would take place if the light emitted during each period had been distributed evenly over the whole duration of the period. This is the Talbot-Plateau law.

Plateau constructed a disk with alternate white and black sectors, and another entirely white. These he placed at different distances from a light so that when rotating both appeared equally bright. If N be the number of white sectors and W the width of each in degrees, the total length of white is N W. If the rotating disk situated at a distance r from the light presents the same intensity as a disk entirely white at a distance R, it follows that

$$\frac{r^2}{R^2} = \frac{N\,W}{360^\circ}$$

The experiments of Plateau accorded well with this law, and Helmholtz also verified it by a variety of experiments.

The latter investigator also applied the principle of the persistence of vision in his acoustical researches, by placing a white spot on a vibrating string or wire. The curve described does not always return upon itself, and therefore by the rapidity of its oscillations the spot will describe a continuously changing curvilinear path. If the luminous intensity of the moving point is constant, but its velocity varies in its path, as will be the case when several motions are compounded, the luminous line will appear brightest where the rapidity is least. In this way the component motions may be resolved.

Helmholtz also discusses in detail the effects produced upon the appearance of moving bodies such as falling drops of water, under the influence of intermittent illumination of various degrees of rapidity.

In regard to the persistence of colored lights Helmholtz contrasts the times given above by Plateau with those of Emsmann:

White	*Yellow*	*Red*	*Blue*
0.25 sec.	0.27 sec.	0.24 sec.	0.22 to 0.29 sec

The discrepancy between them is assigned to the differences in intensities, which Helmholtz points out are of the greatest importance. He himself found that with a certain disk composed of equal white and black sectors, the passage of a black sector did not endure more than 0.021 sec. in very intense illumination, and not more than 0.05 sec. in the light of the full moon.

Maxwell employed the principle of the persistence of vision in his extensive researches on color, in which he made use of the colored disks which now are always associated with his name. His purpose was not to determine the peculiarities of the retina with respect to these phenomena of physiological optics which are considered in this paper, and consideration of his experiments therefore may be omitted here.

In his work on *Modern Chromatics* (3rd Ed. p. 206) Rood made suggestions for the study of the persistence of vision of colors, or the critical frequency of flicker, which have since been followed by many investigators. "The duration of the impression on the retina in the case of light of different colors has not yet been studied carefully . . . . Dr. Wolcott Gibbs suggested to the author a method which would probably solve this problem in a satisfactory manner, and which is about as follows: With the aid of a spectroscope a diffraction spectrum is to be presented to the eye in the form of a series of contiguous coloured bands, the division into bands being effected by a suitable diaphragm placed in the eyepiece of the instrument. In front of the slit of the spectroscope a revolving disk with one or more openings should allow the light to enter the instrument; and, by regulating carefully the velocity of rotation, it would be possible to seize the exact moment when one or more of the colored bands ceased to flicker, and presented a steady, uniform appearance. This observation would give correctly the interval during which the impression remained with undiminished strength on the eye, in the case of the selected color."

In 1884 E. L. Nichols carried this suggestion into execution and made the first persistency curve for the spectrum. At that time the electric motor was not available for this purpose and exact measurements were impossible. The method was later employed by Ferry (1892), in Nichols' laboratory, who found that the duration of the color impression, D, at the critical frequency of flicker, was connected with the luminosity, L, of the color, by the relation

$$D = \frac{k}{\log L}$$

Ferry also found that the values of D were the same for normal eyes, except for persons of advanced age, and that in color-blind eyes the values of D were somewhat larger than normal for the parts of the spectrum corresponding to the defective sensations.

In England T. C. Porter, (1902) using a black and white disk illuminated in succession by white light from very low intensities up to 3000 meter-candles, more exactly formulated the law as follows:

$$\frac{1}{D} = N = k \log L + C$$

where k and C are constants.

Porter also found that when the illumination fell to one quarter of a meter-candle both constants were abruptly reduced to about one-half their former values. It has been suggested that above this value of the illumination vision was chiefly with the cones, and below it with the rods, in accordance with the duplicity theory of von Kries.

More recently (1912) Ives proved that Porter's law extended to colors, with suitable changes in the constants.

With this method of study the writer, at the suggestion of Nichols, has investigated many types of color blindness, and also the effects on the retina due to fatigue with colors. These investigations have led to the discovery of reflex visual sensations which have lately been described in this *Journal*.

The chief practical applications of flicker phenomena are the flicker photometer, discovered or invented by Whitman in 1896, by means of which the photometric values of different colors may be accurately compared, and the now universal moving pictures.

In order that this paper may not be unduly extended the numerous researches of many investigators in more recent years are not included. The results of these may be found in the current treatises on color vision, and the papers themselves are readily accessible.

The persistence of vision possesses a far more extended history than most branches of science, and the phenomena which it comprises, though often apparently of a most trivial character, have been found capable of bringing to our knowledge some of the most fundamental principles of color vision, and also of suggesting new reflex characteristics of the nervous system generally.

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THE VARIATION OF VISUAL SENSORY REFLEX ACTION WITH INTENSITY OF STIMULATION

BY

Frank Allen

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THE VARIATION OF VISUAL SENSORY REFLEX ACTION WITH INTENSITY OF STIMULATION*

By Frank Allen

SYNOPSIS

In this paper there is first a brief résumé of former investigations on the Porter Effect in regard to the retinal effects of varying the intensity of the light stimulus.

Seventeen new Porter graphs have been obtained with bright colors, and instead of only two branches that the Porter graphs were believed to have, from three to five were found.

The effect upon the retinal sensitiveness was measured for intensities corresponding to each branch of the graphs. It was found that this consisted of depression or enhancement of the sensitiveness of the retina.

The relation of these discoveries to the following visual phenomena is discussed: The Fechner Paradox, the Purkinje effect, the Receptor process in respect to the Hering, Edridge-Green, Ladd-Franklin and Young theories, the Weber-Fechner law, Equilibrium effects, Invariable colors, the Self light and Sensation process, the Duplicity theory, Reciprocal innervation, and the partial reconciliation of the Young and Hering color theories.

In former papers[1] the writer developed in considerable detail the characteristics of sensory reflex actions in color vision, which were obtained by stimulating the eyes with many spectral colors extending from the wave length .740μ in the red to .410μ in the violet.

The method of making the measurements was fully described in the papers referred to, but may briefly be outlined here. A spectrum of wide dispersion was formed with an acetylene flame as the source of light. By maintaining the gas at a constant pressure the physical brightness of the spectrum may be kept unvarying for months. A sectored disc, rotated in the path of the light, caused the portion of the spectrum under observation to flicker; and the speed of the disc at the critical frequency of flicker, i.e., when the intermittent flashes of light appear just continuous, was accurately measured. From this the duration of a single flash of light of undiminished brightness was computed. A series of measurements on small patches of color of wave lengths suitably chosen over the whole spectrum enabled a persistency curve to be obtained, such as is shown in Fig. 3, which represents the brightness of the standard or reference spectrum to the eye in its normal condition of daylight adaptation.

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* Read at the meeting of the Optical Society of America, Cornell University, Ithaca, New York, October, 1925.

[1] On reflex visual sensations. J.O.S.A. & R.S.I., *7*, p. 583; 1923.
Reflex visual sensations and color contrast. *Ibid.*, p. 913.

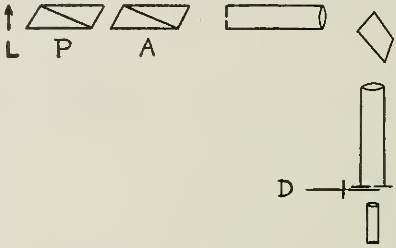

FIG. 1. *Arrangement of apparatus: L, light; P, polariser; A, analyser; D, disc.*

If either eye is then stimulated with a bright monochromatic color and the measurements on the standard spectrum repeated and plotted as a second persistency curve in comparison with the former, any differences between them must be due to the physiological effects of stimulation. According to the Ferry-Porter law,[2] the critical frequency of flicker is determined solely by the brightness of the color and is not affected by the hue. As the physiological brightness depends on the sensitiveness of the visual receptors, the effects of monochromatic stimulation may be determined with great precision and in much detail.

In the former experiments the colors used for stimulation, having been obtained from a very bright arc light spectrum, were very intense. In the papers referred to they were described as approaching whiteness in the central part of the spectrum. This statement is somewhat extreme, as the colors in every case, though very intense, were clearly recognizable. In addition to the actions of colors the effects of stimulation with very bright and very dim white light were also measured. When the left eye was stimulated with bright colors and white light, certain effects were transferred to the right through sensory reflex action, by means of which the retinal receptors corresponding to the three primary colors, red, green and violet, became enhanced in sensitiveness. But when dim white light was used for stimulation in exactly the same way, it produced the opposite effect, and caused the right retinal receptors to be depressed in sensitiveness. This latter effect is known as the Fechner Paradox.

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[2] Ferry, Am. Jour. Sci., *3*, p. 44; 1892.
Porter, Proc. Roy. Soc., *70*, p. 313; 1901.

In a brief review[3] of these papers it was suggested by Dr. Hartridge that the investigation of the Fechner Paradox might be extended to monochromatic stimulation as well. In private communications it was also suggested by Mr. John Tennant, London, that the former researches should be supplemented by studying the effect of stimulation with colors of moderate intensities.

The writer thereupon decided to make the necessary experiments, but in so doing desired to connect the intensities of stimulation with other visual measurements. After much consideration the peculiar phenomenon discovered by Porter[4] for white light, and by Ives[5] for colors, appeared suitable for the purpose. It was found by the former that when the reciprocals of the duration of flashes of white light at the critical frequency of flicker were plotted against the logarithms of the intensity of the light, the graph consisted of two straight lines of different slopes similar to the two lowest branches of the graph in Fig. 2. The intensities of the illuminations used by Porter varied from a few tenths of a meter-candle up to 1600 meter-candles. This result was extended by Ives to spectral colors with similar results, except that the intensities of the colors were not very high.

In both cases the graphs conformed to the equation, found by Porter,

$$1/D = k \log I + C$$

where D is the duration of a single flash of light upon the retina at the critical frequency of flicker, I is the intensity of illumination, and k and c are constants, which have different values for the two branches of the graphs. Later the present writer confirmed[6] the results of Ives, and also concurred in the explanation that the upper branch of the graph represented cone vision for bright light, and the lower rod vision for dim light. This explanation was suggested by the Duplicity Theory of von Kries, with which the two-fold character of the graphs appeared to be completely in harmony.

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[3] Nature, *113*, p. 370; 1924.

[4] Proc. Roy. Soc., loc. cit.

[5] Phil. Mag., *24*, p. 352; 1912.

[6] Phil. Mag., *38*, p. 81; 1919.

Upon consideration, it seemed probable that if the left eye was stimulated by colors whose intensities corresponded to the lower branch of the Porter graphs, the Fechner paradoxical effect would be produced in the right eye; that is, the visual receptors in the right eye would be depressed in sensitiveness, thereby causing the reference spectrum to be perceived less brightly. It was further anticipated that by stimulating the left eye with colors whose intensities corresponded to the upper branch of the graphs, the opposite effect, enhancement of the sensitiveness of the receptors of the right eye, would be produced. Should these effects be realized it would then follow that stimulation by a color corresponding in intensity to the point on the graphs where the change in slope occurred, would produce no effect of either kind.

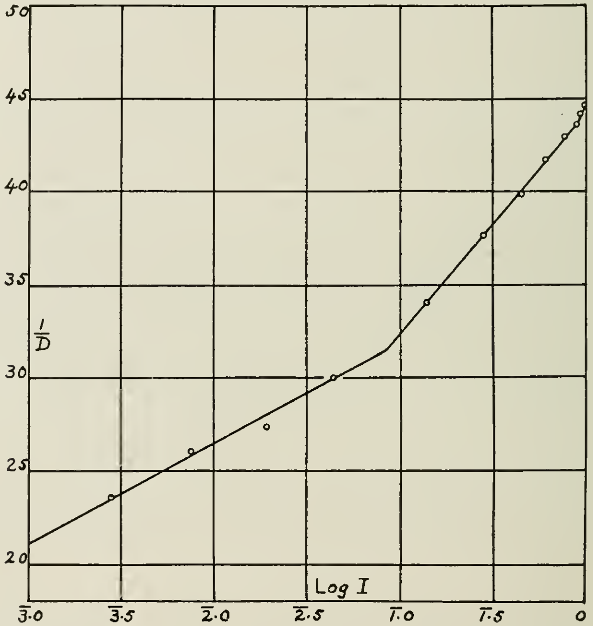

FIG. 2. *Porter graph for wave length .687μ. Acetylene spectrum.*

In the former papers, to which reference has been made, three series of experiments were described. In the first, the effect of stimulation of the left eye upon the corresponding portion of the right was investigated. In the second, the effect of stimulation upon the central area of the right eye, upon which the measurements were always made, was studied. In the third, the effect of stimulation of one portion of the right retina upon a contiguous area was measured.

In the first and third series it was found that the three primary sensations, red, green and violet, were enhanced in sensitiveness, the predominant effect occurring in those complementary to the stimulating color. In the second series the sensation or sensations directly affected were depressed in sensitiveness and the complementary enhanced, the effect again predominating in the latter.

These were the effects anticipated to result from stimulation with color intensities corresponding to the upper branches of the graphs.

In carrying out the experiments the color intensities were controlled by a pair of nicol prisms three centimeters in diameter placed in front of the slit of one of the collimators of the writer's tri color spectrometer.[7] This instrument has three collimators forming three spectra in the same eye-piece. In order to use the same rotating disc and its recording devices with each spectrum, the disc was placed in front of the shutters in a specially designed open Hilger eye-piece. The general arrangement of the apparatus is shown in Fig. 1. The orientation of the analyzer was such that the vibrations of the transmitted light were horizontal. Only the polarizer was rotated so as to vary and measure the intensity of the transmitted ray, which is proportional to the square of the cosine of the angle, θ, between the principal planes of the nicols. The experiments were all performed in daylight so that the unstimulated eye could

TABLE 1. *Porter effect for .687μ. Left hand spectrum.*

Angle between planes $=\theta$	$\cos^2\theta$	$\log \cos^2\theta$	D sec.	$1/D$
0°	1	0	0.0224	44.6
8° 30′	0.978	$\bar{1}.990$	.0226	44.2
18° 30′	.899	$\bar{1}.954$	.0230	43.5
28° 0′	.779	$\bar{1}.892$	.0233	42.9
38° 0′	.621	$\bar{1}.793$	.0240	41.7
48° 0′	.448	$\bar{1}.651$	.0251	39.8
58° 0′	.281	$\bar{1}.448$	.0266	37.6
68° 0′	.140	$\bar{1}.147$	.0294	34.0
78° 0′	.043	$\bar{2}.636$	.0333	30.0
82° 0′	.0194	$\bar{2}.287$	.0366	27.3
85° 0′	.0076	$\bar{3}.881$	.0385	26.0
87° 0′	.0027	$\bar{3}.437$	.0422	23.7
88° 30′	.0007	$\bar{4}.837$	.0487	20.5

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[7] J.O.S.A. & R.S.I., 8, p. 339; 1924.

be maintained in daylight adaptation. All measurements described in this paper were made with the central part of the right eye.

In the first experiments an acetylene flame was used, and with it the Porter graph in Fig. 2 was obtained for the selected red color, .687μ. The measurements are given in Table 1. After this graph was obtained it became possible to stimulate the eye with colors whose intensities corresponded to any branch, and thereby to discover what characteristics were peculiar to each. This graph is composed of two long well marked branches and the beginning of a third, the two points of which were regarded at first as slightly inaccurate readings. The lowest branch has been termed the α branch, or the range of intensities the α intensities, and the others the β and γ.

The curves representing the results of retinal stimulation are usually shown in the form of the persistency curve in Fig. 3, where the broken line is the normal or reference curve for the eye in ordinary daylight adaptation, and the continuous line is for the same eye, and represents the result of stimulation. In the lower part of the figure the same curves are reproduced in another form. The normal readings everywhere are given an arbitrary value of 100, and the others are reduced in the same proportion. This latter method of representation shows still more

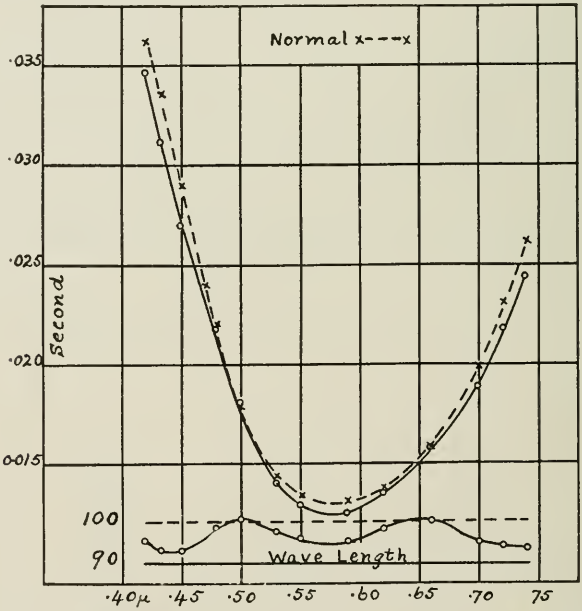

FIG. 3. *Effect of stimulating the right eye with red, .687μ, of β-intensity, I=0.179.*

closely the differences between the curves, and the effect of stimulation may be more accurately estimated. Where the curve obtained after stimulation is above the normal, it shows that that color has become physiologically less bright, and that the corresponding color sensation has been depressed in sensitiveness; where it is below the normal, it indicates that the color has become physiologically brighter than normal, and therefore that the color sensation is enhanced. By this method, which is adopted throughout this paper, all the curves obtained after stimulation with one color at different intensities can be arranged for comparison in a single figure.

EFFECTS OF RETINAL STIMULATION

When the left eye was stimulated with the color .687μ of an intensity ($I=0.015$) corresponding to a point in the lower branch of the graph in Fig. 2, depression of the receptors of all three fundamental sensations in the right eye was produced, a result which is exactly in accordance with the Fechner Paradox. The curve obtained is that marked A in Fig. 4. When the right eye was stimulated with the same color, but of a

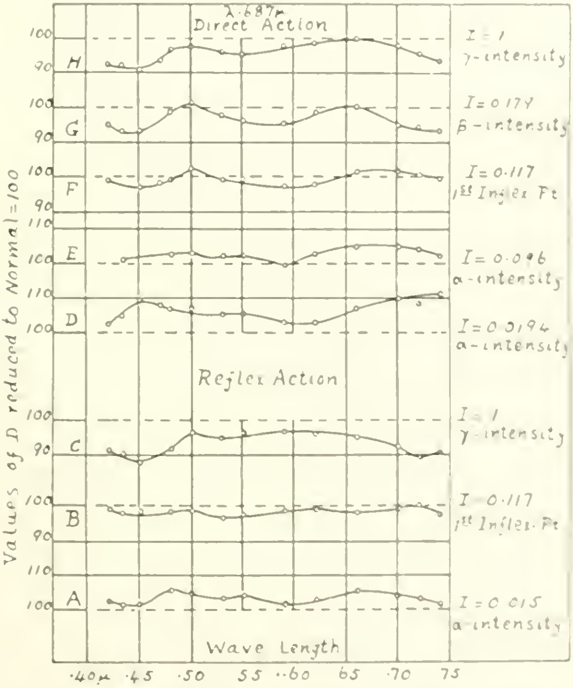

FIG. 4. *Direct and reflex effects of stimulating the right and left eyes with the wave length .687μ at different intensities.*

slightly greater intensity ($I=0.0194$), a similar curve, *D*, Fig. 4, was obtained.

When the intensity of the stimulus was raised from 0.0194 to 0.096, but still corresponding to the lowest branch of the Porter graph, the same type of curve, *E*, Fig. 4, resulted, though the elevations above the normal are not as high as those in curve *D*.

The three curves have one elevation extending from the beginning of the red to about wave length $.590\mu$, and a second extending from that point over the rest of the spectrum. The second elevation shows indications of being composed of two parts corresponding to the green and violet regions of the spectrum.

When the left eye was stimulated with the same red color but of full intensity, the visual receptors in the right eye became reflexly enhanced in sensitiveness, an effect just the opposite of that previously obtained. This is shown by the curve *C* in Fig. 4, which lies wholly below the normal. Similar results were obtained when the right eye was stimulated with intensities corresponding to the intermediate and highest branches of the Porter graph, which are shown in curves *G* and *H* in Fig. 4. With both intensities the three color sensations are enhanced in sensitiveness, and the threefold division of the curves at the wave lengths $.660\mu$ and $.500\mu$ is well marked. Curve *G* is also shown in the persistency curve in Fig. 3.

Since stimulation with color of α intensity produced depression of sensitiveness of the visual receptors, and with color of β intensity enhancement, it seemed probable that stimulation with the color of an intensity ($I=0.117$) corresponding to the point where the change of slope occurs would produce no effect of either kind. Curve *B*, Fig. 4, shows the reflex action obtained in the right eye after stimulation of the left. It is marked by three slight depressions indicating enhancement of the three sensations. Curve *F*, in the same figure, shows the effect when the right eye was stimulated directly. In this case the red sensation is slightly reduced in sensitiveness, and the green and violet sensations are enhanced. Evidently there is an intensity of the stimulus which gives the transition from one type of action to the other, though the intensity used was evidently a little too high. Curve F, however, shows that the reversal of actions may not occur for the three sensations at the same intensity of stimulation.

The measurements for the eight curves just discussed are given in Table 2 for the right eye, and in Table 3 for the left.

TABLE 2. *Right eye stimulated with .687μ. Arc-light spectrum*

λ	N Normal (a) sec.	I = 1 (a intensity) sec.	Reduced N = 100	I = 0.179 (a intensity) sec.	Reduced N = 100	I = 0.117 [illegible] sec.	Reduced N = 100
.740μ	0.0262	0.0248	94.5	0.0244	93.1	0.0260	99.2
.720	.0231	.0220	95.3	.0218	94.2	.0233	100.9
.700	.0199	.0195	98.0	.0189	95.0	.0203	102.0
.660	.0158	.0158	100.0	.0159	100.5	.0160	101.2
.620	.0138	.0136	98.5	.0136	98.6	.0136	98.6
.590	.0131	.0128	97.7	.0125	95.5	.0128	97.8
.550	.0134	.0128	95.5	.0129	96.3	.0133	99.3
.530	.0144	.0138	95.8	.0141	98.0	.0143	99.3
.500	.0179	.0175	97.8	.0181	101.0	.0184	102.9
.480	.0220	.0213	96.7	.0218	99.0	.0219	99.5
.470	.0240	.0224	93.3			.0237	98.8
.450	.0290	.0263	90.6	.0270	93.0	.0283	97.5
.433	.0335	.0310	92.5	.0312	93.2		
.420	.0362	.0336	92.8	.0347	95.8	.0360	99.5

λ	I = 0.096 a intensity sec.	Reduced N = 100	I = 0.019 a intensity sec.	Reduced N = 100
.740μ	0.0268	102.3	0.0292	111.5
.720	.0242	104.8	.0251	108.6
.700	.0209	105.0	.0219	110.0
.660	.0166	105.0	.0170	107.5
.620	.0142	103.0	.0142	103.0
.590	.0131	100.0	.0136	103.8
.550	.0137	102.2	.0142	106.0
.530	.0147	102.2	.0152	105.6
.500	.0185	103.3	.0193	107.8
.480	.0226	102.8	.0236	107.2
.470	. . .	. . .	.0260	108.2
.450	. . .		.0304	104.8
.433	.0338	101.0	.0352	105.0
.420	. . .		.0373	103.0

In the experiments described in the papers to which reference has been made, it was found that when the right eye was stimulated with colors from an arc light spectrum, one or two sensations were always rendered less sensitive and the others enhanced. With the red color .687μ the red sensation was depressed in sensitiveness and the green and violet enhanced. This is shown as curve *D*, Fig. 8, which is reproduced here from the original paper. The data and reference are given in Table 6.

TABLE 3. *Left eye stimulated with .687μ. Acetylene spectrum.*

λ	N Normal sec.	$I=1$ γ-intensity sec.	Reduced $N=100$	$I=0.117$ 1st Infl.Pt. sec.	Reduced $N=100$	$I=0.015$ α-intensity sec.	Reduced $N=100$
.740μ	0.0262	0.0237	90.5	0.0255	97.3	0.0266	101.6
.720	.0231	.0206	89.1	.0232	100.5	.0239	103.3
.700	.0199	.0184	92.5	.0198	99.5	.0208	104.2
.660	.0158	.0150	95.0	.0155	98.1	.0167	105.7
.620	.0138	.0133	96.3	.0137	99.3	.0142	103.0
.590	.0131	.0127	97.0	.0129	98.5	.0133	101.5
.550	.0134	.0129	96.3	.0131	97.7	.0140	104.3
.530	.0144	.0137	95.0	.0139	96.5	.0149	103.5
.500	.0179	.0173	96.6	.0176	98.3	.0188	105.0
.480	.0220	.0201	91.4	.0216	98.2	.0232	105.5
.450	.0290	.0253	87.2	.0285	98.3	.0294	101.3
.433	.0335	.0302	90.2	.0328	98.0	.0340	101.4
.420	.0362	.0332	91.7	.0359	99.2	.0370	102.3

In the experiments that have just been described, all three sensations were enhanced with the brightest light available from the acetylene flame through the nicol prisms. It was obvious, therefore, that the Porter graph must have other branches with brighter light. Since Porter's original graph obtained with white light consisted of only two branches up to intensities of about 1600 meter-candles, it was inferred that different colors would behave differently in their retinal effects, and that Porter's graph represented the combined results of all colors. Experiments with the acetylene flame, therefore, were discontinued, and in its place a 250 watt projection lamp was used, the current being supplied by a storage battery of 110 volts. The current in the lamp was kept at a constant value by an assistant while all further measurements were taken. This light was much brighter than the gas flame; though the nicol prisms with their principal planes parallel reduced its available intensity by one half.

It was decided, therefore, to obtain Porter graphs for colors throughout the spectrum. Seventeen colors were investigated as fully as experimental conditions permitted. The measurements are given in Table 4 and the corresponding graphs are shown in Figs. 5 and 6, the former containing those for the colors from .700μ to .570μ, and the latter those from .570μ to .410μ, the graph for .570μ appearing in each figure.

TABLE 4. *Far periphery*

θ Degrees	Intensity $\cos^2\theta$	$\log \cos^2\theta$	700μ D sec.	700μ 1/D	687μ D sec.	687μ 1/D	660μ D sec.	660μ 1/D
0°	1	0	0.0185	54.1	0.0154	64.9	0.0148	67.6
10	0.970	$\bar{1}.987$	.0188	53.2	.0157	63.7	.0150	66.7
20	.883	.946	.0191	52.4	.0162	61.7	.0151	66.2
30	.750	.875	.0197	50.8	.0171	58.5	.0154	64.9
40	.587	.768	.0206	48.5	.0179	55.9	.0158	63.3
50	.413	.616	.0218	45.9	.0185	54.1	.0165	60.6
60	.250	.398	.0232	43.1	.0195	51.3	.0171	58.5
70	.117	.068	.0254	39.4	.0217	46.1	.0195	51.3
75	.067	$\bar{2}.826$	.0280	35.7	.0229	43.7	.0214	46.7
80	.030	.479	.0312	32.1	.0261	38.3	.0235	42.6
82	.019	.287	.0338	29.6	.0280	35.7	.0244	41.0
84	.011	.038	.0354	28.3	.0298	33.6	.0259	38.6
86	.0049	$\bar{3}.688$	.0377	26.5	.0328	30.5	.0287	34.8
87	.0027	.437			.0356	28.1	.0320	31.3
88	.0012	.085	. .	.			.0348	28.7
89	.0003	$\bar{4}.486$	. .	. .				

θ	.650μ D sec.	.650μ 1/D	.640μ D sec.	.640μ 1/D	630μ D sec.	630μ 1/D	590μ D sec.	590μ 1/D
0°	. . . . . .	. . . .	0.01410	70.9	0.01349	74.1	0.01249	80.1
10	0.0142	70.4	.01415	70.7	.01362	73.4		
20	.0143	69.9	.01428	70.0	.01360	73.5	.01265	79.1
30	.0145	68.5	.01438	69.5	.01370	72.9	.01295	77.2
40	.0150	66.7	.01450	69.0	.01395	71.7	.01333	75.0
50	.0152	65.8	.01462	68.4	.01405	71.2	.01348	74.2
60	.0154	64.9	.0148	67.6	.0144	69.4	.0138	72.5
70	.0170	58.8	.0159	62.9	.0148	67.6	.0142	70.4
75	.0183	54.6	.0168	59.5	.0157	63.7	.0145	69.0
80	.0207	48.3	.0182	54.9	.0172	58.1	.0157	63.7
82	.0222	45.0	.0190	52.6	.0183	54.6	.0168	59.5
84	.0242	41.3	.0206	48.5	.0196	51.0	.0179	55.9
86	.0277	36.1	.0223	44.8	.0220	45.5	.0202	49.5
88	.0340	29.4	.0267	37.5	.0275	36.4	.0244	41.0
89	. . . . . .	. . .	. . . . . .	. . . .			.0298	33.6

TABLE 4. *Continued.*

θ	$.572\mu$		$.570\mu$		$.550\mu$		$.520\mu$	
	D sec.	$1/D$	D sec.	$1/D$	D sec.	$1/D$	D sec.	$1/D$
0°	0.0121	82.6	0.01157	86.4	0.01242	80.5	0.0132	75.8
10	......	....	....	....	.01249	80.1	.0132	75.8
20	.0122	81.9	.01163	86.0	.01275	78.4	.01335	74.9
30	.0124	80.6	.01172	85.3	.01312	76.2	.0134	74.6
40	.0125	80.0	.01178	84.9	.0132	75.8	.0135	74.1
50	.0128	78.1	.0120	83.3	.0134	74.6	.0136	73.5
60	.0133	75.2	.0126	79.4	.0138	72.5	.0143	69.9
70	.0140	71.4	.0134	74.6	.0143	69.9	.0154	64.9
75	.0148	67.6	.0142	70.4	.0151	66.2	.0166	60.2
80	.0158	63.3	.0155	64.5	.0166	60.2	.0181	55.2
82	.0166	60.2	.0162	61.7	.0174	57.5	.0191	52.4
84	.0178	56.2	.0173	57.8	.0186	53.8	.0203	49.3
86	.0195	51.3	.0191	52.4	.0208	48.1	.0232	43.1
87	......	....	.0206	48.5	....	....	.0255	39.2
88	.0233	42.9	.0233	42.9	.0246	40.7	.0302	33.1

θ	$.505\mu$		$.480\mu$		$.450\mu$		$.425\mu$	
	D sec.	$1/D$	D sec.	$1/D$	D sec.	$1/D$	D sec.	$1/D$
0°	0.0140	71.4	0.0161	62.1	0.0218	45.9	0.0256	39.1
10	.0141	70.9	....	....	.0222	45.0	.0258	38.8
20	.0142	70.4	.0165	60.6	.0227	44.1	.0265	37.7
30	.01443	69.3	.0169	59.2	.0237	42.2	.0271	36.9
40	.0148	67.6	.0180	55.6	.0244	41.0	.0288	34.7
50	.0152	65.8	.0187	53.5	.0256	39.1	.0303	33.0
60	.0159	62.9	.0203	49.3	.0277	36.1	.0338	29.6
70	.0175	57.1	.0223	44.8	.0309	32.4	.0381	26.2
75	.0184	54.3	.0250	40.0	.0347	28.8	.0431	23.2
80	.0206	48.5	.0277	36.1	.0382	26.2	.0511	19.6
82	.0219	45.7	.0298	33.6	.0410	24.4	....	....
84	.0235	42.6	.0329	30.4	....	....	....	....
86	.0271	36.9	.0375	26.7	....	....	....	....
87	.0304	32.9	.0409	24.4	....	....	....	....
88	.0352	28.4	....	....	....	....	....	....

TABLE 4. *Concluded*

θ	.420μ		.410μ	
	D sec.	1/*D*	*D* sec.	1/*D*
0°	0.0274	36.5	0.0343	29.2
20	.0280	35.7	.0347	28.8
30	.0290	34.5	.0360	27.8
40	.0312	32.0	.0372	26.9
50	.0334	29.9	.0397	25.2
60	.0362	27.6	.0420	23.8
70	.0408	24.5	.0439	22.8
75	.0445	22.5	...	...

A wide diversity of actions of colors is revealed by these figures. The graphs for the red colors from .700μ and probably from the beginning of the spectrum, to nearly .660μ, consist of three branches. The

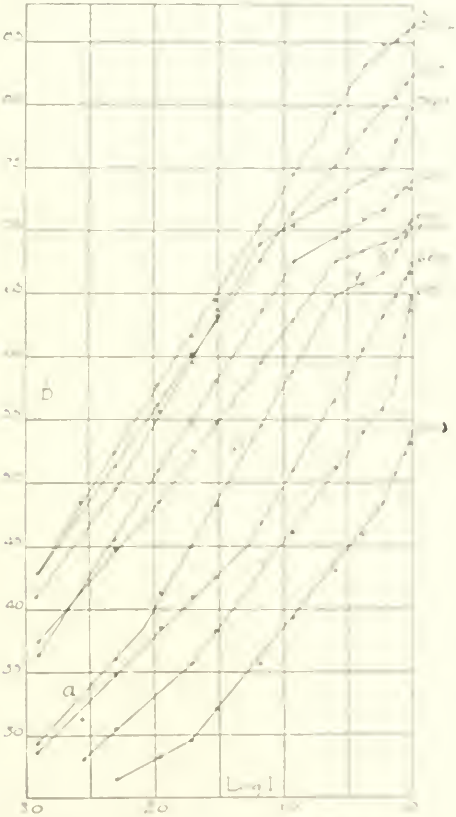

FIG. 5. *Porter graphs for the red, orange and yellow colors.* $I = \cos^2\theta$.

graph for .660μ has but two branches, though the uppermost four points indicate a slight tendency to form two more branches somewhat like the graph for .650μ.

From .660μ nearly to .572μ the graphs possess four branches. It is interesting to note how greatly the graphs change with but slight variations in wave length. This is shown in the series for the hues .660μ, .650μ, .640μ, .630μ, and .590μ. With the color .572μ the graph resumes the two-fold character, though in that for .570μ the upper branch is very short. It will be noticed that four graphs in Fig. 5 intersect. This evidently indicates that the lamp was not kept quite at constant brightness while the measurements were being made. Had the brightness been absolutely constant no intersections could have occurred.

In proceeding to the shorter wave lengths, striking differences are again found in the graphs in Fig. 6. With the color .550μ, four branches

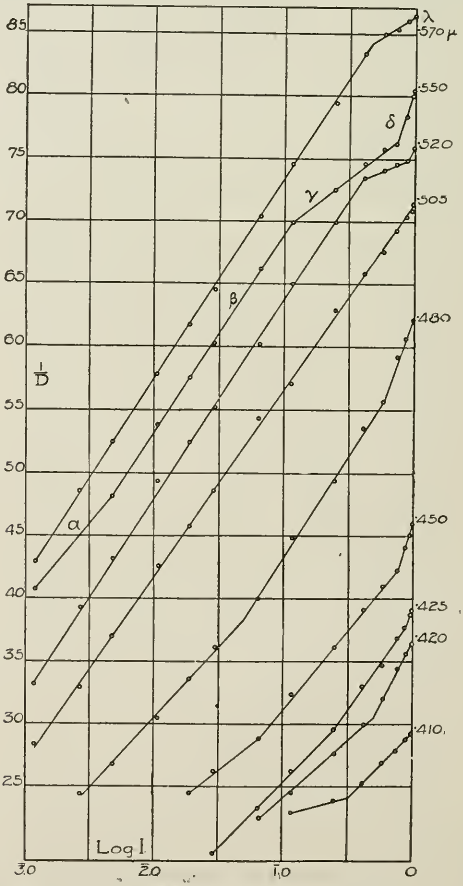

FIG. 6. *Porter graphs for the green, blue and violet colors.* $I = \cos^2 \theta$.

are obtained, that for $.520\mu$ has but three, while the graph for $.505\mu$ is remarkable in being a single straight line. A close examination of the points in the upper part of the graph indicates, however, a slight tendency to divide in branches. From the wave length $.480\mu$ to $.425\mu$ three branches are found, and in the remainder only two.

In his investigations Ives[8] had found that with blue and violet colors the lowest branch was horizontal. Later this was confirmed by the present writer.[9] In the present investigation no color has this characteristic. The difference is probably due to the fact that the present experiments were made with the eyes in daylight adaptation, while the former investigations were conducted in the customary dark room.

Though no graph was found to possess more than four branches, evidence will shortly be given to indicate the probability of a fifth branch being found with some of the spectral colors.

In analogous investigations by the writer and his assistants on the senses of touch[10] and taste,[11] similar Porter graphs consisting of three branches were obtained; while in sound,[12] Porter graphs with two branches resulted from measurements over a short range of intensities. It is evident, therefore, that in obtaining these graphs we are dealing with the most fundamental and general characteristics of sensory actions.

In referring to these graphs it will be convenient to term them, as has already been done, the Porter graphs, and the phenomenon they represent the Porter effect, since that investigator discovered it. As there are four, and probably five, branches of some of the graphs, a convenient mode of distinguishing them must be devised. Following the suggestion of my colleague, Professor J. F. T. Young, Greek letters have been selected. The lowest branch of the graph for each color may therefore be termed the α branch and the remainder the β, γ, δ, and ϵ branches. The intensities corresponding to these branches may similarly be termed the α intensity, or the α spectrum, etc. One graph in each figure has its four branches properly marked.

The point between the α and β branches at which the change of slope occurs may be termed the *first inflexion point*; and similarly for the others, the *second* and *third inflexion points*.

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[8] Phil. Mag., *24*, p. 352; 1912.

[9] Phil. Mag., *38*, p. 81; 1919.

[10] Allen and Hollenberg. The Tactile Sensory Reflex. Quar. Jour. Exp. Physiol., *14*, p. 351; 1924.

Allen and Weinberg, *Ibid.*, *15*, p. 377; 1925.

[11] Allen and Weinberg. The Gustatory Sensory Reflex, *Ibid.*, *15*, p. 385; 1925.

[12] Phil. Mag., *47*, p. 941; 1924.

The interpretation of the Porter graphs when only two branches were known was in harmony with the Duplicity Theory of von Kries. The α branch was supposed to represent rod or scotopic vision, and the upper, or β branch, cone or photopic vision. In this explanation the writer had concurred. It is obvious, however, that this explanation can no longer be admitted on account of the number of branches of the graphs, and also on account of the existence of similar graphs from analogous measurements on other senses which do not possess any two-fold receptor mechanism, such as rods and cones. A lengthy series of experiments was now carried out to determine the cause of the Porter effect. For this purpose ten colors were selected, which were used at various intensities for stimulating the left eye, the right eye, and an area of the right eye adjoining that upon which measurements were made. Including the eight which have already been discussed, forty-four persistency curves have been obtained in this investigation in order to provide a sufficiently wide basis for such conclusions as are warranted. The intensity of stimulation employed is marked on each curve and in the tables. By referring to these and to Table 4 and the Porter graphs in Figs. 5 and 6, the branch of the graph to which each intensity belongs may be recognized. This, however, is also indicated on each curve.

In each of the Figs. 4 and 7 to 12, inclusive, the intensity of one curve is marked $I=1$. This does not mean that these intensities are all of the same value, but only that the intensity of the color was that of the spectrum when the principal planes of the nicols were parallel.

WAVE LENGTH .700μ (TABLE 5, FIG. 7)

With the color .700μ the direct action of stimulation of the right eye was measured for two intensities. Curve F shows the effect of β intensity stimulation, which is the enhancement of the red, green and violet sensations, though in this case the last is scarcely affected. When color of δ intensity was used—curve G—the red sensation was still enhanced and the green and violet were depressed in sensitiveness. As the Porter graph for this color has three branches, the middle one may be regarded as consisting of the β and γ branches which are of the same slope, and therefore form a continuous line. It will be seen later that stimulation with β and γ intensities produces effects of the same type but not of the same magnitude.

TABLE 5, *Stimulation with .700μ*

λ	D Normal sec.	I = 0.883 δ-intensity sec.	Reduced D = 100	I = 0.117 β-intensity sec.	Reduced D = 100
.740μ	0.0258	0.0251	97.4	0.0249	96.5
.720	.0233	.0225	96.5	.0222	95.2
.700	.0209	.0208	99.5	.0211	101.0
.660	.0171	.0175	102.3	.0170	99.5
.620	.0147	.0148	100.6	.0145	98.6
.590	.0138	.0140	101.5	.0135	97.7
.550	.0143	.0146	102.0	.0138	96.6
.530	.0153	.0154	100.8	.0147	96.0
.500	.0191	.0200	104.7	.0189	99.0
.480	.0233	.0244	104.8	.0234	100.5
.450	.0292	.0306	104.8	.0294	100.8
.433	.0330	.0346	105.0	.0332	100.6
.420	.0363	.0381	105.0	.0361	99.5

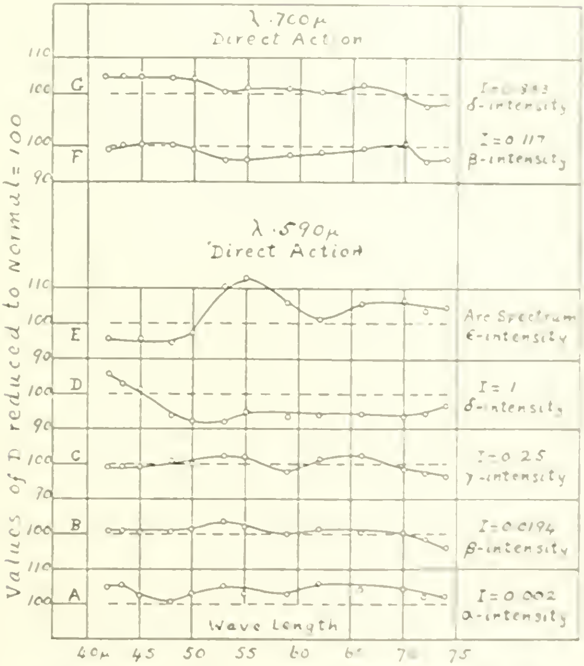

FIG. 7. *Effect of stimulating the right eye with the wave lengths .700μ and .590μ.*

WAVE LENGTH .687μ (TABLE 6, FIG. 8)

The effects of stimulation with .687μ of low intensities have been already discussed and shown in Fig. 4. With the brighter light a curve,

TABLE 6. *Right eye stimulated with .687μ.*

λ	N Normal sec.	$I=1$ δ-intensity sec.	Reduced $N=100$	$I=0.725$ 2nd Inf.Pt. sec.	Reduced $N=100$	$I=0.067$ β-intensity sec.	Reduced $N=100$	Arc ε-intensity *
.740μ	0.0258	0.0240	93.0	0.0246	95.2	0.0255	98.7	106.3
.720	.0233	.0220	94.5	.0225	96.6	.0227	97.6	104.2
.700	.0209	.0199	95.4	.0202	96.6	.0203	97.2	107.0
.660	.0171	.0168	98.2	.0170	99.5	.0167	97.7	101.2
.620	.0147	.0148	100.8	.0143	97.3	.0142	96.6	98.0
.590	.0138	.0143	103.6	.0134	97.0	.0133	96.4	95.3
.550	.0143	.0150	105.0	.0143	100.0	.0141	98.6	94.8
.530	.0153	.0156	102.0	.0150	98.0	.0148	96.7	94.5
.500	.0191	.0201	105.2	.0193	101.0	.0188	98.5	98.5
.480	.0233	.0253	108.4	.0232	99.5	.0235	100.8	99.5
.450	.0292	.0322	110.2	.0294	100.7	.0292	100.0	97.0
.433	.0330	.0362	109.5	.0335	101.5	.0327	98.0	93.2
.420	.0363	.0388	107.0	.0367	101.0	.0365	100.5	95.4

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., *7*, p. 601; 1923.

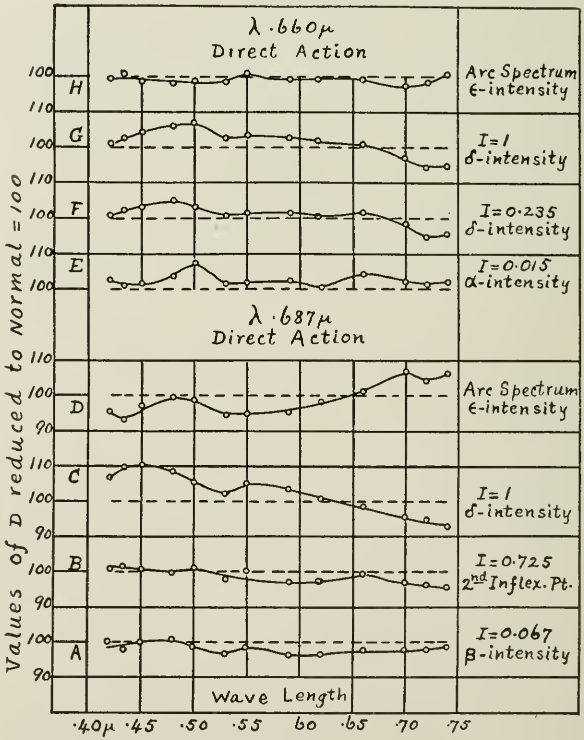

FIG. 8. *Effect of stimulating the right eye with the wave lengths .660μ and .687μ.*

A, for β intensity, was obtained. This shows enhancement of nearly the whole spectrum. Stimulation with color of an intensity corresponding to the second inflexion point (curve *B*) shows enhancement of the red and green sensations, while the violet is slightly depressed. This effect is more characteristic of the third inflexion point. As the Porter graph for .687μ has three branches, the middle one probably consists of the β and γ branches with no point of inflexion between them. Stimulation with color of δ intensity (curve *C*) shows marked enhancement of the red and depression of the green and violet sensations. Curve *D* shows the effect of the same color obtained from an arc spectrum, which is provisionally termed ϵ intensity. This shows the opposite effect which is the depression of the red sensation and enhancement of the green and violet.

In these figures all curves marked *arc spectrum* are reproduced from a former investigation to which reference is made in the tables.

WAVE LENGTH .660μ (TABLE 7, FIG. 8)

In former investigations it was found that the color .660μ gave neither depression nor enhancement of the sensations, and was termed an equilibrium color. The Porter graph, however, consists of two long branches. Curve *E* shows the effect of direct stimulation with color of α intensity, which is the depression of all three sensations. Two other

TABLE 7. *Right eye stimulated with .660μ.*

λ	N Normal sec.	$I=1$ δ intensity sec.	Reduced $N=100$	$I=0.235$ δ intensity sec.	Reduced $N=100$	$I=0.015$ α-intensity sec.	Reduced $N=100$	Arc spectrum ϵ-intensity *
.740μ	0.0258	0.0245	95.0	0.0247	95.7	0.0263	102.0	101.0
.720	.0233	.0221	94.7	.0221	94.7	.0237	101.7	98.2
.700	.0209	.0203	97.1	.0206	98.5	.0213	102.0	97.2
.660	.0171	.0173	101.1	.0174	101.8	.0178	104.0	99.5
.620	.0147	.0150	102.0	.0148	100.7	.0148	100.7	99.4
.590	.0138	.0142	102.8	.0140	101.3	.0141	102.3	99.4
.550	.0143	.0148	103.5	.0145	101.4	.0146	102.0	101.2
.530	.0153	.0157	102.8	.0154	100.7	.0155	101.3	98.7
.500	.0191	.0205	107.2	.0197	103.0	.0205	107.2	99.0
.480	.0233	.0247	106.0	.0245	105.0	.0242	103.9	98.4
.450	.0292	.0305	104.3	.0301	103.0	.0297	101.7	99.0
.433	.0330	.0340	103.0	.0337	102.2	.0333	101.0	101.0
.420	.0363	.0367	101.0	.0366	101.0	.0373	102.8	99.5

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., 7, p. 601; 1923.

intensities gave results characteristic of the δ intensity stimulation—curves F and G—which are the enhancement of the red sensation and depression of the green and violet. It is quite evident, therefore, that this is not an equilibrium color, except at the highest intensities. The significance of this result will be discussed later.

WAVE LENGTH .590μ (TABLE 8, FIG. 7)

The direct action of the yellow color, .590μ, for five intensities is shown in the figure. The depressing effect of α intensity stimulation is well marked in curve A. Curves B and C show that stimulation with β and γ intensities produces similar results almost equilibrium in character. The higher δ intensity, curve D, shows marked enhancement

TABLE 8. *Stimulation with* .590μ.

λ	N Normal sec.	$I=1$ δ-intensity sec.	Reduced $N=100$	$I=0.25$ γ-intensity sec.	Reduced $N=100$	$I=0.0194$ β-intensity sec.	Reduced $N=100$	$I=0.002$ α-intensity sec.	Reduced $N=100$
.740μ	0.0258	0.0250	96.9	0.0248	96.1	0.0248	96.1	0.0265	102.7
.720	.0233	.0220	94.4	.0227	97.5	.0230	98.7	.0239	102.5
.700	.0209	.0195	93.4	.0205	98.1	.0210	100.5	.0219	104.8
.660	.0171	.0161	94.2	.0175	102.3	.0172	100.7	.0178	104.1
.620	.0147	.0138	94.0	.0149	101.4	.0149	101.4	.0156	106.0
.590	.0138	.0129	93.5	.0135	98.0	.0138	100.0	.0142	103.0
.550	.0143	.0136	95.0	.0146	102.0	.0146	102.0	.0148	103.5
.530	.0153	.0141	92.0	.0157	102.7	.0158	103.2	.0161	105.2
.500	.0191	.0176	92.1	.0191	100.0	.0194	101.5	.0197	103.1
.480	.0233	.0219	94.0	.0235	101.0	.0235	101.0	.0235	101.0
.450	.0292	.0296	101.3	.0289	99.0	.0294	100.7	.0300	102.8
.433	.0330	.0340	103.0	.0328	99.4	.0333	101.0	.0348	105.5
.420	.0363	.0384	105.9	.0362	99.6	.0366	101.0	.0380	105.0

Arc spectrum ε-intensity*			
λ		λ	
.740μ	104.8	.530μ	110.9
.720	103.4	.500	97.5
.700	106.5	.480	94.5
.660	105.8	.450	95.5
.620	101.2	.433	.....
.590	106.0	.420	95.7
.550	113.0		

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., 7, p. 601; 1923.

of the red and green sensations and depression of the violet, while the arc spectrum, curve *E*, gave the exact opposite which is the depression of the red and green sensations and enhancement of the violet.

WAVE LENGTH .570μ (TABLE 9, FIG. 9)

With these results the direct action of the color .570μ may be compared. In a former investigation[13] with an arc spectrum, it was found that almost the same color, .572μ, gave equilibrium effects. The three

TABLE 9. *Stimulus .570μ*

λ	N Normal sec.	*I*=1 α-intensity sec.	Reduced N=100	*I*=0.067 α-intensity sec.	Reduced N=100	*I*=0.008 α-intensity sec.	Reduced N=100	Arc Spectrum equivalent*
.740μ	0.0258	0.0254	98.4	0.0254	98.4	0.0262	101.4	99.0
.720	.0233	.0229	98.3	.0238	102.2	.0257	101.8	100.7
.700	.0209	.0205	97.0	.0211	101.0	.0210	100.5	100.3
.660	.0171	.0169	98.8	.0173	101.1	.0173	101.1	98.5
.620	.0147	.0151	102.7	.0151	102.7	.0151	102.7	98.7
.590	.0138	.0135	97.7	.0138	100.0	.0140	101.3	98.6
.550	.0143	.0140	98.0	.0141	98.6	.0144	100.7	99.4
.530	.0153	.0153	100.0	.0156	102.0	.0155	100.0	101.2
.500	.0191	.0187	97.9	.0194	101.5	.0194	101.5	97.5
.480	.0233	.0229	98.3	.0235	100.8	.0231	99.0	98.0
.450	.0292	.0290	99.3	.0294	100.8	.0293	100.3	97.6
.433	.0330	.0332	100.5	.0334	101.2	.0331	100.2	96.5
.420	.0363	.0370	102.0	.0369	101.8	.0368	101.3	99.4

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., 7, p. 601; 1923.

curves *F*, *G* and *H*, in the figure, however, indicate that the former hue gives equilibrium effects down to the lowest intensity. Apparently with low intensities .570μ is an equilibrium color, while with high, .572μ has that characteristic, since curve *I*, obtained with .570μ in the arc spectrum, shows some enhancement of the green and violet sensations.

WAVE LENGTH .550μ (TABLE 10, FIG. 10)

With the green color .550μ, a more lengthy series of six persistency curves was taken. Curve *A* shows the reflex depressing effect upon the right eye of α intensity stimulation of the left, while curve *B* shows the direct action of the same stimulus upon the right eye. Both show depressing effects of the same type but not of the same magnitude,

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[13] J.O.S.A. & R.S.I., 7, p. 913; 1923.

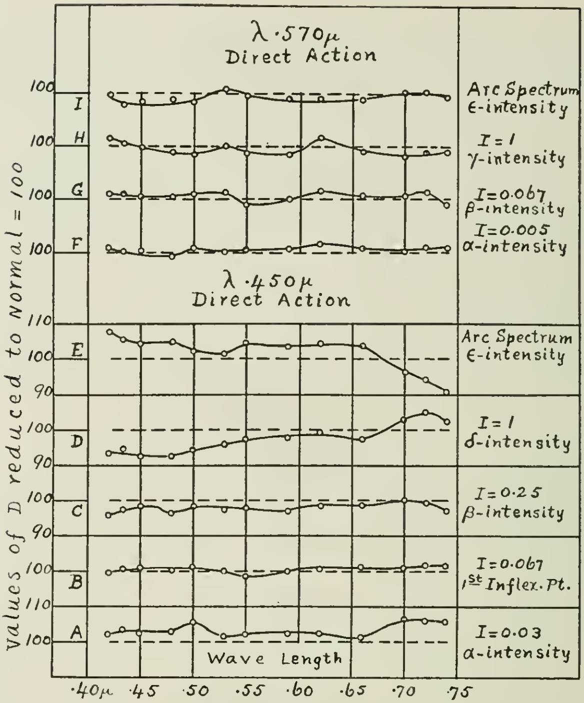

FIG. 9. *Direct effect of stimulating the right eye with the wave lengths .570μ and .450μ.*

TABLE 10. *Stimulation with .550μ.*

	Direct Action						
λ	N Normal sec.	$I=1$ δ-intensity sec.	Reduced $N=100$	$I=0.413$ γ-intensity sec.	Reduced $N=100$	$I=0.019$ β-intensity sec.	Reduced $N=100$
.740μ	0.0258	0.0267	107.2	0.0253	98.0	0.0252	97.7
.720	.0233	.0243	104.2	.0232	99.6	.0228	98.0
.700	.0209	.0215	103.0	.0209	100.0	.0205	98.0
.660	.0171	.0168	98.3	.0166	97.2	.0166	97.2
.620	.0147	.0144	98.0	.0145	98.6	.0145	98.6
.590	.0138	.0133	96.4	.0134	97.0	.0132	95.6
.550	.0143	.0136	95.2	.0139	97.2	.0136	95.2
.530	.0153	.0143	93.5	.0146	95.4	.0145	94.8
.500	.0191	.0179	93.7	.0181	94.7	.0180	94.3
.480	.0233	.0223	95.6	.0220	94.4	.0216	92.6
.450	.0292	.0294	100.7	.0288	98.6	.0276	94.5
.433	.0330	.0347	105.0	.0325	98.5	.0332	97.5
.420	.0363	.0384	105.8	.0362	99.7	.0354	97.5

λ	Direct Action				Reflex Action Left Eye		Arc spectrum intensity*
	I=0.005 1st Inf Pt sec.	Reduced N=100	I=0.0012 (α-intensity) sec.	Reduced N=100	I=0.0012 α-intensity sec.	Reduced N=100	
.740μ	0.0261	101.1	0.0265	102.0	0.0264	102.3	87.5
.720	.0231	99.2	.0241	103.5	.0248	102.2	99.4
.700	.0210	100.5	.0224	107.2	.0212	107.4	88.0
.660	.0169	98.8	.0181	109.8	.0178	104.0	93.4
.620	.0148	100.8	.0152	107.1	.0150	104.0	90.4
.590	.0137	99.3	.0141	101.4	.0144	107.4	101.5
.550	.0139	97.2	.0150	104.0	.0139	109.0	100.0
.530	.0145	94.8	.0166	108.1	.0164	107.1	110.2
.500	.0185	96.8	.0206	107.8	.0201	105.2	80.0
.480	.0229	98.3	.0215	105.2	.0237	101.8	90.2
.450	.0290	99.4	.0296	101.5	.0306	102.8	80.7
.433	.0331	100.3	.0336	101.8	.0341	105.7	
.420	.0368	101.4	.0381	107.0	.0375	103.0	94.5

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., 7, p. 601; 1923.

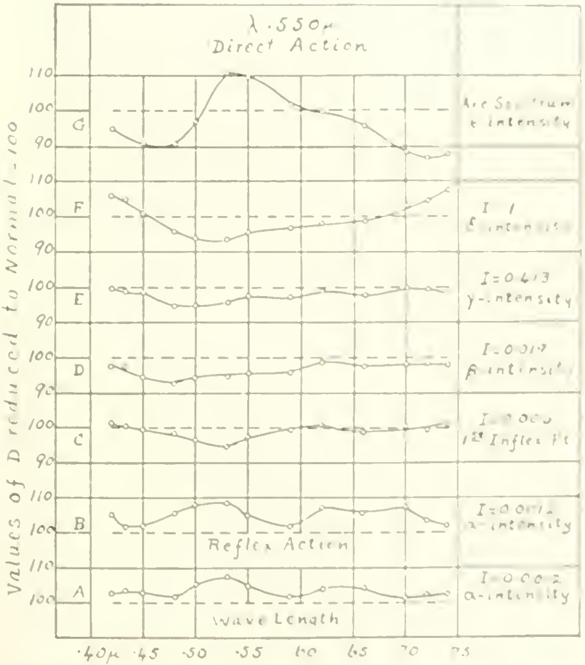

FIG. 10. *Direct and reflex effects of stimulating the right eye with the wave length .550μ.*

the direct action, as might be expected, having the greater effect. The intensity corresponding to the first inflexion point, as nearly as it could be determined from the Porter graph, gives the equilibrium condition in the red and violet sensations, but enhances the green, as shown in curve *C*. Evidently the intensity selected is a little too high, since enhancement of the green sensation has occurred which is characteristic of β intensity stimulation. The curves, *D* and *E*, for β and γ intensities, show enhancement of the whole spectrum. When the color was used at δ intensity, curve *F*, the green sensation was enhanced and the red and violet depressed. With the very bright color from the arc spectrum, ϵ intensity, exactly the opposite effect occurred as is shown by curve *G*. It is to be noted that in curves *A*, *B* and *C*, coincidence with the normal occurs at about the wave length .590μ, while in the remainder it occurs nearer the red.

WAVE LENGTH .505μ (TABLE 11, FIG. 11)

The most remarkable Porter graph was obtained with the color .505μ, which gave a single straight line. This indicates that all branches have the same slope. In the original measurements for stimulation with this color from an arc spectrum, coincidence with the normal resulted, as is shown in curve *I*. The new curves *F*, *G* and *H*, for lower

TABLE 11. *Stimulation with* .505μ.

λ	N Normal sec.	$I=1$ γ-intensity sec.	Reduced $N=100$	$I=0.117$ β-intensity sec.	Reduced $N=100$	$I=0.005$ α-intensity sec.	Reduced $N=100$	Arc spectrum ϵ-intensity *
.740μ	0.0258	0.0259	100.4	0.0260	100.8	0.0260	100.8	98.0
.720	.0233	.0235	101.0	.0230	98.6	.0235	101.0	99.0
.700	.0209	.0211	101.0	.0207	99.0	.0213	102.0	99.5
.660	.0171	.0170	99.4	.0170	99.4	.0173	101.0	100.0
.620	.0147	.0148	100.6	.0146	99.4	.0148	100.6	100.0
.590	.0138	.0138	100.0	.0137	99.3	.0140	101.4	99.3
.550	.0143	.0141	98.5	.0141	98.5	.0144	100.8	99.4
.530	.0153	.0148	96.8	.0152	99.4	.0155	101.2	98.2
.500	.0191	.0188	98.4	.0193	101.0	.0192	100.5	97.5
.480	.0233	.0230	98.6	.0232	99.5	.0231	99.1	98.7
.450	.0292	.0295	101.0	.0289	99.0	.0287	98.3	99.6
.433	.0330	.0334	101.1	.0331	100.2	.0333	100.9	.....
.420	.0363	.0365	100.4	.0355	97.7	.0358	98.0	99.5

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., 7, p. 601; 1923.

intensities, show the equilibrium condition to be a characteristic of the color for all intensities.

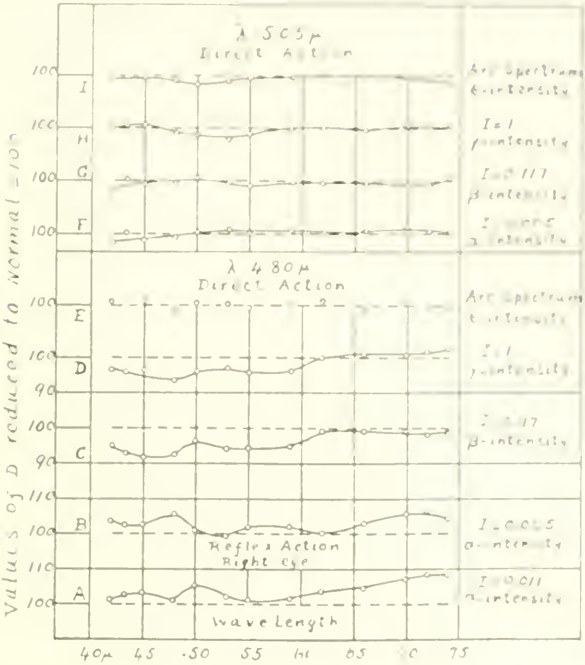

FIG. 11. *Direct and reflex effects of stimulating the right eye with the wave lengths .505μ and .480μ.*

WAVE LENGTH .480μ (TABLE 12, FIG. 11)

The color .480μ is also an equilibrium color at high intensities, as is shown by curve *E*. This color at α intensity was used to stimulate one side of the right retina and the effect was measured on a contiguous area in the manner used by the writer in experiments performed to determine the cause of contrast. The result of the present measurements is exhibited in curve *A*, which shows depression of the whole spectrum. A similar result, curve *B*, was obtained when the stimulation was upon the retinal area with which measurements were made. Curves *C* and *D* give the effects of stimulation with β and γ intensities, which show enhancement of the green and violet sensations, but scarcely any effect upon the red. It is evident, therefore, that this color only possesses equilibrium characteristics at the highest intensities.

TABLE 12. *Stimulation with* .480μ.

		Direct action						Reflex action	
λ	N Normal sec.	$I=1$ γ-intensity sec.	Reduced $N=100$	$I=0.117$ β-intensity sec.	Reduced $N=100$	$I=0.005$ α-intensity sec.	Reduced $N=100$	$I=0.011$ α-intensity sec.	Reduced $N=100$
.740μ	0.0258	0.0265	102.7	0.0255	98.8	0.0269	104.3	0.0280	108.3
.720	.0233	.0238	102.0	.0228	98.0	.0249	106.8	.0253	108.7
.700	.0209	.0211	101.0	.0207	99.1	.0221	105.7	.0225	107.5
.660	.0171	.0173	101.2	.0170	99.3	.0176	103.0	.0179	104.8
.620	.0147	.0147	100.0	.0146	99.3	.0147	100.0	.0153	104.0
.590	.0138	.0133	96.4	.0131	95.0	.0141	102.2	.0140	101.5
.550	.0143	.0137	95.7	.0135	94.4	.0146	102.0	.0143	101.3
.530	.0153	.0149	97.3	.0144	94.0	.0152	99.3	.0156	102.0
.500	.0191	.0184	96.3	.0185	96.7	.0193	101.0	.0201	105.2
.480	.0233	.0218	93.5	.0216	92.6	.0246	105.5	.0236	101.3
.450	.0292	.0281	96.3	.0269	92.0	.0299	102.4	.0302	103.2
.433	.0330	.0317	96.0	.0307	93.0	.0338	102.3	.0339	102.8
.420	.0363	.0351	96.7	.0345	95.0	.0376	103.6	.0369	101.7

Arc spectrum ϵ-intensity*			
λ		λ	
.740μ	99.4	.550μ	99.4
.720	99.5	.530	100.0
.700	101.2	.500	100.4
.660	98.3	.480	98.7
.620	101.3	.450	101.4
.590	100.0	.420	101.0

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* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., *7*, p. 601; 1923.

WAVE LENGTH .450μ (TABLE 11, FIG. 9)

With the color .450μ, α intensity stimulation, curve A, depresses the retinal sensations. Intensity of the first inflexion point, curve B, shows complete equilibrium. The δ intensity stimulation, curve C, shows

TABLE 11. Stimulation with .450μ

λ	λ Normal sec.	I=1 α-intensity sec.	Reduced N=100	I=0.25 [illegible] sec.	Reduced N=100	[illegible] sec.	Reduced N=100	[illegible] sec.	Reduced N=100
.740μ	0.0258	0.0265	102.7	0.0250	97.0	0.0263	101.7	0.0271	105.0
.720	.0233	.0245	105.1	.0231	99.2	.0235	101.0	.0247	106.0
.700	.0209	.0215	103.0	.0209	100.0	.0211	101.0	.0222	106.2
.660	.0171	.0167	97.6	.0169	98.7	.0173	101.2	.0175	102.3
.620	.0147	.0146	99.3	.0145	98.6	.0148	100.8	.0150	102.1
.590	.0138	.0135	97.8	.0134	97.0	.0138	100.0	.0141	102.2
.550	.0143	.0139	97.3	.0140	98.0	.0141	98.7	.0146	102.0
.530	.0153	.0147	96.0	.0149	97.4	.0153	100.0	.0155	101.3
.500	.0191	.0180	94.2	.0188	98.4	.0193	101.0	.0202	105.8
.480	.0233	.0216	92.6	.0225	96.5	.0233	100.0	.0240	103.0
.450	.0292	.0271	92.8	.0287	98.3	.0295	101.0	.0299	102.3
.433	.0330	.0313	94.8	.0322	97.6	.0333	100.8	.0341	103.3
.420	.0363	.0341	93.8	.0349	96.0	.0362	99.6	.0370	102.0

Arc spectrum
ε intensity*

λ		λ	
.740μ	91.0	.530μ	101.8
.720	94.4	.500	102.3
.700	96.7	.480	104.8
.660	104.0	.450	104.4
.620	104.6	.433	105.5
.590	103.4	.420	108.0
.550	104.5		

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., 7, p. 601; 1923.

enhancement of all three sensations. Curve D, however, exhibits enhancement of the violet and green sensations and depression of the red, which are characteristic of stimulation with δ intensity.

WAVE LENGTH .410μ (TABLE 14, FIG. 12)

The reflex action of the color .410μ, of α intensity when applied to one side of the retina of the right eye is shown in curve A; and when applied to the left eye in curve B. The direct action on the right eye is shown in curve C. All three curves indicate that the sensitiveness of the three fundamental sensations is depressed. The curve obtained with an intensity corresponding to the second branch of the Porter graph is shown in curve D. The enhancement of the violet and green

TABLE 14 *Stimulation with* .410μ

λ	N Normal Sec.	Direct action				Reflex action			
						Left eye		Right eye	
		$I=1$ β-intensity Sec.	Reduced $N=100$	$I=0.25$ α-intensity Sec.	Reduced $N=100$	$I=0.178$ α-intensity Sec.	Reduced $N=100$	$I=0.25$ α-intensity Sec.	Reduced $N=100$
.740μ	0.0258	0.0268	104.0	0.0279	108.0	0.0267	103.3	0.0276	107.0
.720	.0233	.0241	103.2	.0256	109.8	.0237	101.8	.0251	107.7
.700	.0209	.0208	99.5	.0232	111.0	.0214	102.3	.0219	104.8
.660	.0171	.0160	93.5	.0175	102.3	.0169	98.0	.0176	103.0
.620	.0147	.0139	94.5	.0156	106.0	.0145	98.6	.0152	103.3
.590	.0138	.0133	96.4	.0145	105.0	.0141	102.2	.0141	102.2
.550	.0143	.0138	96.5	.0148	103.5	.0145	101.3	.0144	100.8
.530	.0153	.0147	96.0	.0159	104.0	.0155	101.3	.0153	100.0
.500	.0191	.0190	99.4	.0217	113.5	.0197	103.0	.0197	103.0
.480	.0233	.0231	99.0	.0260	111.3	.0244	104.9	.0236	101.3
.450	.0292	.0275	94.2	.0320	109.6	.0302	103.3	.0300	102.8
.433	.0330	.0321	97.2	.0349	105.8	.0340	103.0	.0333	101.0
.420	.0363	.0343	94.5	.0376	103.6	.0367	101.0	.0374	104.0

Arc spectrum ϵ-intensity*			
λ		λ	
.740μ	95.2	.530μ	95.2
.720	96.7	.500	98.5
.700	97.5	.480	106.0
.660	99.0	.450	109.0
.590	96.0	.433	108.0
.550	94.2	.420	106.6

* Reduced from Table 4 in paper "On Reflex Visual Sensations," J.O.S.A. & R.S.I., *7*, p. 601, 1923.

sensations is characteristic of γ intensity stimulation, but the depression of the red sensation indicates δ intensity. This curve, therefore, is somewhat anomalous in character. It is similar to curve *D*, Fig. 9, for the blue color .450μ, which is compounded of the violet and green sensations. The violet color has hitherto shown all the characteristics of a simple sensation. This is indicated in curve *E*, Fig. 12, where the violet sensation is depressed, and the green and red enhanced.

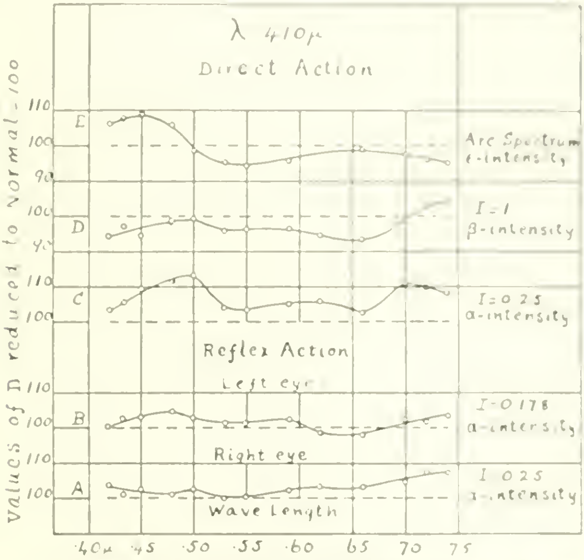

FIG. 12. *Direct and reflex effects of stimulating the right and left eyes with wave length .410μ.*

SUMMARY OF RESULTS

The forty-four new persistency curves which have now been described were obtained during a period of about eight months, under variable conditions of cloud and sunlight. The changes of season and of daylight illumination, together with probable variations in the physical condition of the writer, would all have some effect upon the measurements obtained. On some days experimentation of this type is conducted with great ease; on others the readings were obtained with greater difficulty. It is not surprising, therefore, that the curves are not always of the same decisive character in every detail. Of the fifty three curves in the figures, thirty-five show indications of a three-fold division corresponding to the red, green and violet colors; twelve clearly show equilibrium effects; and six, while not showing divisions, yet indicate appropriate enhancement or depression of the spectrum in whole or in part. The evidence afforded by the persistency curves therefore strongly supports the trichromatic theory of color vision.

Excepting only the equilibrium colors, .570μ and .505μ, stimulation with colors of α intensity always results in depression of the sensitiveness of the three primary sensations, whether the action of the color is directly upon the retinal area with which measurements were made, or whether that area is affected by the reflex action of the stimulus from an adjoining part of the same retina, or from the other eye.

Stimulation with colors whose intensities correspond to the first inflexion point results in equilibrium conditions between the enhancing and depressing effects due to the action of the stimulus.

Stimulation with colors of β intensity always produces enhancement of all three sensations. This is also true of γ intensity stimulation where it is known to be such.

Stimulation with colors of δ intensity causes enhancement of the sensation or sensations directly concerned in the color sensation, and depression of the complementary; while the higher intensities, termed ϵ intensities, cause the opposite effect.

The second inflexion point between the β and γ intensities is not an equilibrium intensity, but denotes a change in the ratio of the magnitudes of the depressing and enhancing impulses. Only one persistency curve (*B*, Fig. 8) for an intensity of this nature was obtained.

Color intensity corresponding to the third inflexion point between the γ and δ intensities should, apparently, indicate partial equilibrium conditions with reference to the complementary of the color of the stimulus. Since, however, the characters of δ intensity and ϵ intensity stimulation are opposite, it would appear to follow that the fourth inflexion point between them would be of equilibrium intensity like the first. No persistency curves of either of these intensities, the third and fourth inflexion points, have yet been obtained.

It follows, therefore, that all colors can produce equilibrium effects if of proper intensities. This has been observed by Emerson and Martin[14] in their investigations on the photometric matching field; though the underlying causes are only now determined.

It has been customary from the standpoint of vision to regard colors as stimuli which varied only in hue, saturation and intensity. The study of the Porter graphs and the persistency curves shows clearly that, in addition, colors are stimuli possessed of varying physiological powers, dependent upon hue and intensity, of evoking reflex activities. Apparently each branch of a Porter graph represents a definite ratio of the enhancing and depressing impulses which for some reason changes in value at a definite intensity of stimulation, and which differs with each color. If each chromatic sensation were completely independent, the Porter graphs for all colors would likely be the same. Since, however, three sensations are invariably involved in every color stimulation, complications are inevitable which the Porter graphs reveal.

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[14] Proc. Roy. Soc. A., *108*, p. 483; 1925.

The highly varied character of the Porter graphs for different colors indicates also what little value the study of white light has in determining the principles which govern the operation of the visual apparatus. Since white light is a mixture of all the spectral colors, stimulation by it involves an extraordinary variety of direct and reflex actions, any one of which may change in character by a slight change in the hue or intensity of some component color.

Martin[15] has also pointed out that if illuminants are deficient in blue and violet, the retinal receptors will be deprived of the powerful enhancing influences of these colors. Not only will this be true, but if any color is present only at α intensity, enhancement will be replaced by depression, which, as we have seen, will still further detrimentally affect the perception of the whole spectrum.

The enhancement of all three primary sensations which results from stimulation with colors of β, γ and δ intensities has evidently an important bearing on certain kinds of experiments performed by many observers. Stimulation by a color of any intensity is usually assumed to fatigue the one or the two sensations directly affected, whereas with moderate intensities the opposite effect occurs. It has doubtless often happened that when an experimenter believed he was fatiguing his eye with some color, he was in reality enhancing its sensitiveness, with the result that an erroneous inference must have been drawn from the experiment. The fact that stimulation of the retina can produce opposite effects according to the intensity employed will no doubt explain some of the contradictory observations made by different observers.

The predominant depressing influence of α intensity stimulation has an important practical application. When the illumination falls below the intensity of the first inflexion point the dim light depresses the retinal sensitiveness. This effect superposed on the feeble illumination must seriously impair the visual power. This shows the necessity of avoiding shadows in industrial lighting, and also indicates that the minimum illumination in mines, for example, should be above the first inflexion point.

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[15] Cantor Lecure I. Roy. Soc. Arts, p. 17: 1925.

THEORETICAL CONSIDERATIONS

The results of these experiments may thus be generalized. Every light stimulus acting upon the retina, generates in the visual receptors nervous impulses which ascend by the afferent nerves to the visual centers in the cortex where a sensation of light and color is produced. At some point in the reflex arc, probably in the synaptic junctions of the afferent and efferent nerves, additional nervous impulses are evoked, which descend by the efferent nerves to all parts of both retinas, by means of which the sensitiveness of the visual receptors is controlled. These efferent impulses are of two kinds, one of which enhances and the other depresses the sensitiveness of the receptors. The result of these actions is the production of a state of sensitiveness which is the measure of the excess of one process over the other. The receptors themselves when stimulated by light give a three-fold response, resulting in the production of three fundamental color sensations corresponding to the red, green and violet colors of the spectrum. Every ray of light stimulates all three color sensations in varying degrees, and the efferent impulses generally depress or enhance the sensations also in varying amounts.

THE FECHNER EFFECT

When a color stimulus of α intensity falls upon either retina, the sensitivity of the whole system of visual receptors in both eyes is depressed. This is shown by the curves which have been described. In a former investigation[16] a similar result was obtained with white light of low intensity. It was further discovered that while darkness depresses the sensitivity to a considerable extent, dim light depresses it still more.

There is a long known but hitherto unexplained phenomenon which illustrates the depressing influence of stimuli of low intensities. This is termed the Fechner paradox. When, for example, a piece of white paper sufficiently illuminated is viewed by the right eye while the left is closed, the sudden entrance of weak light through smoked glass into the left eye causes the white paper to appear darker to the right. The unexpected action of light of one intensity in weakening the perception of light of another intensity evidently led to the use of the word paradox.

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[16] Phys. Rev., *11*, p. 265; 1900. J.O.S.A. & R.S.I., *7*, p 608; 1923.

The binocular interactions between two lights are thus summarized by Myers[17]: "The brightness of the combined image of two steady flickerless lights, respectively thrown on corresponding retinal areas, is obviously not equal to the sum of the two brightnesses. Its value is usually slightly above the arithmetical mean of the brightness of the uniocular components, provided that these do not differ too widely from one another. When the components are equally bright the binocular increase has been variously extimated to be from one-tenth to one-thirtieth. It appears, however, that the increment rises with the degree of dark adaptation.

"Thus if the uniocular images differ in brightness, the binocular brightness becomes considerably less than the brighter of the uniocular components. This result is known as Fechner's paradox. It reaches its maximum when the two brightnesses are in the ratio 1:25. When they are in the ratio 1:1.5, the binocular brightness is about equal to that of the brighter component. . . . It is absent when the darker of the two fields is presented before the brighter, and when the area of the former is made considerably smaller than that of the latter."

Since the nervous actions associated with, or forming part of, the visual process, and indeed of all sensory processes, are now more fully ascertained, one of which is the depressing effect of weak stimulation, the Fechner paradox may more properly be termed the Fechner effect; for in the very nature of science the word "paradox" has no permanent place in connection with any of its phenomena.

The Fechner effect is the normal depressing action of the α spectrum, and should therefore be obtained with all monochromatic illumination of α intensity, except the equilibrium colors, of which there appear to be at least two in the α spectrum, $.570\mu$ and $.505\mu$. As the first inflexion point in each Porter graph represents an equilibrium intensity for the color concerned, no Fechner effect should be obtained with them also.

Since experiments show that α intensity stimulation of one retinal area causes depression of sensitiveness of the adjoining areas, it follows that the Fechner effect should be observed uniocularly, under conditions similar to those in the binocular experiments. This appears to have been observed by Hering.[18]

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[17] Experimental Psychology, Part I, 2nd Ed., p. 270.

[18] Sherrington. Integrative Action of the Nervous System, p. 375.

The Fechner effect, as Myers points out, is not of the same magnitude with all ratios of intensities of the binocular components. The persistency curves, which have been discussed, indicate quite characteristic differences in the results of β, γ, δ and ϵ stimulation. There can be very little doubt that these differences are sufficient to account for all variations in the magnitude of the Fechner effect.

Should the darker component be viewed first its depressing effect upon the other eye will immediately result, and in consequence the bright field at the very first glance will be seen at the lowered intensity. It is probably incorrect, therefore, to say that the Fechner effect is absent when the procedure is reversed; it is present, but the depression of sensitiveness having already occurred before the bright field is viewed, the change of the intensity from one brightness to another cannot be observed.

When the weakly stimulated area is very small it is evidently unable to counteract the enhancing influence of the brighter light on a larger area. This probably explains why the Fechner effect is not observed under these conditions.

It seems not unlikely that under proper conditions the sudden admission of the brighter component into one eye would raise the intensity of the darker in the other, and so produce a reversed Fechner effect.

It also appears improbable that the Fechner effect should exist with two fields each of which is illuminated with either white light or colors of α intensity, unless different intensities produced depressions of different magnitudes.

It seems quite evident that the binocular brightness of uniocular components will be complicated by the fact that β, γ, δ and ϵ intensities have individual characteristics which differ from each other. When white light is used the resultant effect of many simultaneous monochromatic influences is at present impossible to predict.

Sherrington[19] has elaborately investigated the binocular perception of white light under different conditions. The researches of the writer, however, have been so largely confined to colors that they do not afford an adequate basis for a discussion of the somewhat intricate results obtained with white light.

This investigation of the causes of the Fechner effect shows that it is due to the reciprocal actions of unequal stimuli upon corresponding retinal areas of the two eyes; or, as suggested above, upon contiguous retinal areas in one eye. This is precisely what the writer has found to occur in simultaneous contrast.[20] It clearly follows, therefore, that the Fechner effect or paradox is merely a special case of simultaneous binocular luminosity contrast, in which one component is of low intensity, viewed under conditions which enable the contrast darkening process to be observed.

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[19] Loc. cit., p. 371, sqq.

Phenomena exactly like the depressing effect of *a* intensity stimulation have been obtained by the writer and Miss Weinberg[21] in the sense of taste. For in researches on that sense by analogous methods, similar Porter graphs consisting of three branches were found which conformed to the equation:

$$1/D = -k \log Q + C$$

where Q is the quantity of the gustatory stimulus; whereas in vision the equation of the Porter graphs is

$$1/D = k \log I + C.$$

When a weak solution of sugar was placed on one side of the tongue, the gustatory receptors on the other side were depressed in sensitiveness; but when the solution was strong enhancement occurred.

In touch, Allen and Hollenberg[22] have shown that precisely the opposite effect occurred. In this sense similar measurements gave the equation:

$$D = -k \log P + C$$

where P is the intensity of the tactile stimulus.

In audition[23] an equation similar to this was found to hold:

$$D = k \log P + C$$

where P is the intensity of the sound employed.

From this it is inferred that in the latter two sensory actions weak stimuli would have an enhancing influence upon the receptors, and strong a depressing effect. The former has been verified in touch, but not yet in sound; the latter occurs in both.

It would appear to be generally true, therefore, that in those senses in which the Porter graphs require the reciprocal of D, the Fechner effect occurs; but where the graphs involve D directly, the Fechner effect is reversed.

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[20] J.O.S.A. & R.S.I., *7*, p. 913; 1923.

[21] The Gustatory Sensory Reflex. Quar. Jour. Exp. Physiol., *15*, p. 385, 1925.

[22] The Tactile Sensory Reflex, Quar. Jour. Exp. Physiol., *14*, p. 351, 1924. Also *15*, p. 377; 1925.

[23] On the Critical Frequency of Pulsation of Tones, Phil. Mag., *47*, p. 941, 1924.

From the experimental evidence given above there seems to be no doubt that the Fechner effect will occur with monochromatic colors. In these cases not only would the darkening effect occur, but very probably it would be accompanied by a change in hue the precise nature of which would depend upon what sensations were predominantly affected. It is quite possible that the changes would not follow the same tendency as is found when colors are of enhancing intensities.

In a previous investigation on the cause of color contrast,[24] the reciprocal influence of stimulated retinal areas upon each other was measured. The results generally were in harmony with what had been found by many observers. In this paper it has been shown that certain differences in their effects occur when the intensities of retinal stimuli vary from one branch of the Porter graphs to another. In general the enhancement, and perhaps the depression, occurs predominantly in the sensations complementary to the color of the stimulus. It is apparent, however, that a minute study of contrast will show variations in the phenomena observed which will be dependent upon the intensity of the colors, upon their equilibrium character throughout, or upon their equilibrium intensities.

THE PURKINJE EFFECT

It has been found by Haycraft[25] and by Ives[26] with the critical frequency method, that a pronounced shifting of the brightest point of the spectrum towards the green occurred at low intensities. This is the Purkinje effect. Ives investigated it with reference to the Porter graphs, and found that the Purkinje effect was exhibited by the spectrum when its intensity was below the 'first inflexion point, i.e., of α intensity; while for intensities above, a reversed Purkinje effect was observed. It is therefore evident that the effect in question is a characteristic of the α intensity spectrum. It follows that neither the Purkinje effect nor the reverse will occur at an intensity equal to the first inflexion point. With white light Porter found this point at an intensity of 0.25 meter-candle; with colors no photometric measurements of it are yet available.

The explanation of this phenomenon is probably not to be found in the change from cone to rod vision. It seems more likely that at low intensities the green sensation is more isolated from the red than at

[24] J.O.S.A. & R.S.I., *7*, p. 913; 1923.

[25] Jour. of Physiol., *21*, p. 126; 1897.

[26] Phil. Mag., *24*, p. 352; 1912. Also, Parsons, Colour Vision, 2nd Ed., pp. 62 and 106.

high. It is no doubt significant in this connection that the point of coincidence of the persistency curves with the normal is about .59μ for α intensity stimulation, whereas at high intensities it is about .65μ. It is noteworthy that Maxwell found the transition point between red and green to be at .581μ, and Burch at .573μ.

In this connection it may again be pointed out that all the Porter graphs and persistency curves described in this paper were obtained with the central part of the retina, where rods are not to be found or are fewer in number than the cones. In the fovea itself, which contains only cones, the Purkinje effect is either entirely absent or is very small. The present experiments therefore seem to be in opposition to the view that the Purkinje effect is due to differences between rod and cone vision.

König[27] has obtained normal luminosity curves of the spectrum for eight different intensities. The brightest of these had its maximum luminosity at the wave length .610μ and the lowest at .535μ. As the brightest point is usually found at about .590μ, König's observations show the Purkinje effect and its reverse for steady light.

If a dim spectrum—brighter than α intensity—is viewed when flickering, the Purkinje effect is reversed and the brightest point is moved towards the red. This may be accounted for by the greater rapidity with which the red sensation is aroused compared with the green, and also, and perhaps most of all, by the greater development of the reflex enhancement of the red sensation. This is indicated by measurements of the initial overshooting of the sensations as shown by the curves of Broca and Sulzer.[28] In all their curves the red sensation reaches a greater maximum than the green, the overshooting of the red sometimes being double its normal brightness, while the green never exceeds its normal value. In a flickering spectrum, therefore, the red sensation will predominate causing the brightest point to move in its direction.

When the spectrum is of α intensity, the Purkinje effect is found with a flickering light. This can be explained by assuming, in the absence of measurements, that below the first inflexion point the green sensation develops a greater maximum than the red, and perhaps in a shorter time. If this is the case, then at the critical intensity of the first inflexion point the brightest point will not be moved in either direction in a flickering spectrum.

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[27] Gesammelte Abhandlungen, p. 169. Also, Parsons, loc. cit., p. 49.

[28] Comp. Rend., *2*, p. 1046; 1903. Also, Parsons, loc. cit., p. 96.

The treatment of the Purkinje phenomenon has been naturally but quite needlessly complicated. This has been brought about by the custom of regarding a moderately bright spectrum as a standard with which very dim and very intense spectra must be compared. Hence we have the Purkinje effect and the reversed Purkinje effect under various conditions.

This is quite analogous to the practice of locating a convenient intermediate zero point on the thermometric scale at the melting point of ice, which renders plus and minus readings necessary. The inconvenience is at once obviated by choosing an absolute zero at the lowest possible temperature.

Similarly if a very dim spectrum of α intensity is chosen as the standard, the brightest point will then be in the green. The three fundamental sensations are all gently stimulated, and for some reason the green appears to consciousness the brightest. As the light becomes more intense the response of the sensations increases, and as the red has a more luminous effect than the violet, its influence becomes disproportionately greater, with the result that the brightest point must lie at some point between the red and green, as is commonly observed. On this account the brightest point may shift from .535μ to 610μ as König observed.

THE VISUAL RECEPTOR PROCESS

The general problem of color vision may be divided into five parts. First, the nature and properties of the physical stimulus; second, the nature of the retinal visual receptors and of the process by which light is transformed into nervous impulses; third, the arrangement and functions of the nerves connecting the retina with the cortex; fourth, the nature and functions of the connections between the nerves and the visual centers of the cortex; fifth, the origin and nature of the sensations of color.

The researches of the writer have been concerned with the third part of the problem, and particularly with the efferent nerves and their important functions. These have been elaborated to a very considerable degree, and from them something may now be inferred regarding the receptor and sensation processes constituting the second and fourth parts of the problem.

The new experiments described in this paper show that at least seven characteristic effects are caused in the receptors by a single color stimulus. First, it affects the perception of the spectrum in three parts, red, green and violet; second, low intensity of stimulation depresses the sensitiveness of the receptors of the same three colors; third, medium intensity of stimulation causes enhancement of the receptors of the same three colors; fourth, higher intensity of stimulation causes enhancement of the one or of the two sensations directly concerned and depression of the remainder; fifth, still higher intensity of stimulation causes depression of the one or two sensations corresponding to the color of the stimulus, and enhancement of the complementary remainder; sixth, certain intensities of stimulation have equilibrium characteristics; seventh, stimulation of an area of one retina or of one eye causes depression or enhancement of the sensitiveness of adjoining areas or of the other eye.

A great variety of receptor actions has been assumed by various theorists, only a few of the more important of which need be considered here. Hering's hypothesis postulates the existence of three retinal photochemical substances, two of which are influenced by two pairs of complementary colors, red-green, yellow-blue, and a third by white-black. Two opposite types of action, dissimilation and assimilation of the substances are caused by the first color in each pair and by the second respectively. While Hering assumed the reciprocal action of retinal areas on each other, no suggestion as to how this was accomplished was given by him, and the binocular actions were ignored. With this type of receptor constitution not one of the seven experimentally determined results of stimulation conforms.

Mrs. Ladd-Franklin has devised probably the most detailed receptor action of all, by her assumption of the existence in the retina of a light sensitive molecule which on dissociation by light gives off first a cleavage-product which in turn gives rise to a white sensation in the cortex. The remainder of the molecule thereby becomes capable of giving off two subsidiary cleavage-products for yellow and blue. The yellow is now susceptible of subdivision into two further products, which are capable of exciting the red and green sensations.

On comparing the seven characteristics of stimulation with the assumptions of this hypothesis there seems to be no agreement between them; nor does it seem possible to make so mechanical a receptor process conform to them. The "light-molecule" is in a manner so detached from the nerves that nervous impulses of a reflex character cannot influence its cleavability, especially in such diverse forms as experimental results require.

Edridge-Green's hypothesis has one great virtue in that it does not deal with hypothetical substances, but attempts to assign a function to the visual purple. This rod pigment is assumed to sensitize the cones which are the real percipient elements of vision as far as the retina is concerned. The action of light is considered to be photographic in character. The hypothesis as a whole is non-elemental, but a subsidiary action is provided to bring it into conformity with the facts of trichromasy.

As far as the writer is aware there is nothing in the photographic process comparable to the peculiar enhancing and depressing effects which have been found to be characteristic of color vision. Nor does it seem possible to harmonize the type of receptor activity assumed by this hypothesis with the seven characteristics outlined above.

The various photochemical and photoelectric hypotheses seem generally to be incapable of conforming to the seven visual characteristics. Though no assumptions regarding receptor actions are at present acceptable, the writer finds himself also unable to suggest one. The conditions that have to be met are, however, clear. The receptor process must be in such close and vital union with the visual nerves that the complicated states of sensitivity may be subject to the most immediate and delicate control of the efferent nervous system. Furthermore, as in such diverse senses as touch and taste the same phenomena of depression and enhancement occur, which in the latter are as complicated as in vision, and as their response follows practically the same mathematical law, the visual receptor process must have some characteristics in common with them. Such a process does not appear even to have been imagined; and it is possible that some distinctive receptor action *sui generis* has yet to be discovered before a satisfactory solution of the initial process of vision can be found. It may be the case that the original hypothesis of "three sets of nerves" is closer to the truth than all the more definitely elaborated mechanisms which have been devised to replace them.

THE WEBER-FECHNER LAW

It has always been believed, until the writer has demonstrated the contrary, that the only effect of stimulation of a sensory receptor was to generate an afferent nervous impulse which ascended to the cortex and there caused a sensation. Upon this belief the Weber-Fechner law was formulated.

Following Parsons[29] it may be thus stated: "If S is the measure of sensation and δS the just appreciable difference, I the measure of the stimulus and δI a small increment, then

$$\delta S = k\delta I/I$$

(Weber's law), where k is a constant; therefore, on the questionable assumption that it is permissible to integrate small finite quantities,

$$S = k\int \frac{dI}{I} = k \log I + C \text{ (Fechner's Law)},$$

where C is another constant."

Porter's equation

$$1/D = k \log I + C$$

which is very similar to Fechner's, has been derived independently by Peddie.[30]

If D, the duration of a flash of light at the critical frequency of flicker, is a measure of the sensation, as seems probable, then Porter's and Fechner's equations are identical.

It has been found, when put to the test of measurement, that Fechner's law holds only through a limited range of medium intensities, breaking down with both high and low stimulation. From the experimental results discussed above, the conclusions are justified that the sensitiveness of the visual receptors is under the control of the efferent nervous system, and that sensations are modified by the sensitiveness of the receptors. Fechner's law must therefore in reality express the result of both afferent and efferent nervous actions, instead of the afferent alone. It has just been shown that the ratio of enhancing and depressing effects varies from one branch of the Porter graphs to another, and also that Porter's equation holds for each branch with changes in the values of the constants. The conclusion therefore seems clear that in the case of visual perceptions Fechner's law is accurately followed from extremely low to extremely high intensities of stimulation.

In the investigations, to which reference has been made, on the senses of touch and taste, Porter graphs of three branches, and in the case of audition, of two branches, were also obtained, to which nearly the same form of equation applied. In these senses also Fechner's law accurately holds from very low to, at least, moderately high stimulation.

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[29] Colour Vision, 2nd Ed., p. 23.

[30] Color Vision, p. 162.

The reason why it has been concluded that Fechner's law is valid only for medium intensities is probably because it has been attempted to make a single pair of numerical values of the constants suffice, whereas from two to five pairs are necessary in the four sensoria studied.

EQUILIBRIUM EFFECTS

In former investigations, when the eye was stimulated with very bright colors from an arc-light spectrum, six colors were found that caused neither enhancement nor depression of sensitiveness of the receptors. These were $.660\mu$, $.572\mu$, $.520\mu$, $.505\mu$, $.480\mu$, and $.425\mu$. They were found to occur at or near the points of intersection or the ends of the König and the Abney sensation curves. In the experiments described above, the spectral colors were all of much lower intensities than König and Abney employed. Only two of the seventeen colors used were found to give equilibrum effects at all intensities, which were $.570\mu$ and $.505\mu$. In addition every color is equilibrium in character at the first and fourth inflexion points. These results probably explain the statement of Emerson and Martin,[31] who have found in their experiments that all colors at some intensities give equilibrium effects. This suggests that the sensation curves of König and of Abney, which were obtained with sun-light and arc-light respectively, do not correctly represent the sensations at medium and low intensities. The desirability of determining the sensation curves for several ranges of intensities is therefore apparent.

In former papers it was suggested that equilibrium effects were due to equality of the direct and reflex actions of colors. The experiments which have now been described indicate that two sets of efferent impulses are operating in the visual apparatus, and that the equilibrium is between the enhancing and depressing influences, which counterbalance each other and thereby maintain the sensitiveness of the receptors constant.

INVARIABLE COLORS

When colors are changed in intensity they generally vary to some degree in saturation and hue as well. Changes of this character may also take place upon prolonged fixation, with no change of intensity.

It is known that every color excites the three primary sensations in unequal amounts, and that equal stimulation[32] results in the production of white. The changes in saturation and hue are therefore readily explained as due to variations of the relative sensitivities of the sensations caused by the sensory reflex actions accompanying stimulation, which thereby produce changes in the relative amounts of excitation by direct action of the color. If, however, the color stimulus evokes enhancing and depressing reflex impulses in equal amounts, i. e., if it is an equilibrium color, the degree of excitation of the sensations preserves the same ratio. The saturation, therefore, may change but the hue will remain invariable.

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[31] Proc. Roy. Soc. A., *108*, p. 500; 1925.

It has been found that two colors at least, .505μ and .570μ or some hues very close to these, are equilibrium in character. Hence these should not vary in hue when the intensity rises from the lowest to the highest values.

In regard to these phenomena, Myers[33] may be quoted: "It might be expected that the hue of a colour stimulus would become more intense, the greater the intensity of the stimulus. But, beyond a certain limit, further increase of the intensity of the stimulus causes the corresponding colour sensation to pass over gradually into a colourless sensation. Indeed, any colour stimulus, if sufficiently intense, is seen as white. Intense spectral reds and orange, and greens up to a wave length of .517μ, acquire a yellow hue before they in this way become colourless. A green, of a somewhat shorter wave length than .517μ, can be found, which passes over into white without change of colour tone. Intense colour stimuli, of still shorter wave length, become blue before they become colourless."

Now the equilibrium color .505μ is a green of somewhat shorter wave length than .517μ and may be identified as the invariable color in question. Its equilibrium character is therefore most probably the cause of its invariability in hue. As the colors of longer wave length than .517μ pass through yellow in their progress to white, it follows that there is a yellow color which is itself an invariable hue. The equilibrium color near .570μ may therefore have the property of invariability.

Since, as Myers states, colors of shorter wave length than the invariable green become blue before passing over into white; another equilibrium color may exist in the blue. The Porter graphs do not include any such equilibrium color in the blue; but there is abundant room for one to exist, as a reference to Fig. 6 will show.

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[32] Abney, Researches in Colour Vision, p. 251.

[33] Experimental Psychology, 2nd Ed., Part 1, p. 75.

It has also been shown that four colors preserve their hue invariable when passing from central to peripheral vision. On this account they have been assumed by Hering to be the four fundamental color sensations required by his theory. They are, a purplish-red (non-spectral), a yellow (about $.570\mu$), a bluish-green (about $.490\mu$), and a blue (about $.460\mu$).[34]

The invariable yellow evidently coincides with the yellow equilibrium color of the writer. The hue, $.490\mu$, is not far from the equilibrium color $.505\mu$. In this connection it may be noted that the Hering invariable colors have never been determined with exact spectral hues but with colored papers and gelatine filters. The disagreement in consequence may not be significant. It is possible also that a blue between the wave lengths $.480\mu$ and $.450\mu$ may have equilibrium properties, though the writer has not yet examined this region. However, at high intensities the wave length $.480\mu$ is an equilibrium color.

It may also be noted that the wave length $.500\mu$ was found by both Maxwell and Burch to be the transition point between green and blue.

It may also be remarked here that the two equilibrium colors, $.570\mu$ and $.505\mu$, are practically the boundaries of the central portion of the spectrum for which there are no single complementary colors in the spectrum.

THE SELF LIGHT OF THE RETINA AND THE SENSATION PROCESS

In a former paper[35] on the self light of the retina, the writer endeavored to connect its admittedly central origin from endogenous stimuli[36] with discharges in the efferent portion of the reflex arc. At that time only the enhancing action was known, and the intrinsic light was therefore identified with it.

Recently Emerson and Martin[37] have pointed out that the association of the self light with enhancing impulses is quite the reverse of the view of Helmholtz, in whose mathematical theory the self light reduces the sensation brightness. They further intimate that the writer has gone "farther than the results of his experiments justify, by assuming that the reflex effect also consists of an actual stimulation of the receptor elements besides an enhancement of their sensitiveness to light or that the mathematical "self light" of Helmholtz is not to be identified with the visual appearance which usually goes under the name."

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[34] Parsons, loc. cit., p. 75.

[35] J.O.S.A. & R.S.I., *8*, p. 275; 1924.

[36] Parsons, loc. cit., p. 116.

[37] Proc. Roy. Soc. A., *108*, p. 497; 1925.

The present experiments on the production of reflex effects by a intensity stimulation show that depression of sensitiveness is a characteristic of stimulation of low intensity, and that it results from reflex action, as the binocular experiments prove. The self light is usually of extremely low intensity, and this may indicate its origin to be not in the enhancing but in the depressing reflex impulses, thus bringing it into conformity with Helmholtz's theory. This is much to be desired if only to prevent the possibility of two forms of self light from complicating visual theory.

The association of sensations with efferent nervous impulses involves some obvious difficulties. That these impulses control the sensitiveness of the retinal receptors is clear, but the assumption that they can also arouse sensations requires more definite evidence than is at present available. If they do excite sensations, it must be either by means of the retinal receptors or by some action in the junctions of the afferent and efferent nerves in the cells of the cortex.

The latter supposition may be considered somewhat as follows. The afferent impulses upon reaching their terminals in the cortex arouse sensations, and simultaneously evoke the two kinds of efferent impulses which are conducted to the receptors. This action would involve a transfer of energy from the cortical cells to the efferent nerves, accompanied probably by some form of reaction which would affect consciousness as a sensation. In this way the negative after-images at least, and the self light of the retina, which are believed to be of central origin, might be accounted for, the former perhaps by reactions from enhancing impulses and the latter from the depressing. Possibly, indeed, sensations of all kinds may be due to the energy reactions occurring at the synaptic junctions of the nerves in the cells of the cortex.

As nervous discharges when once started may continue to flow in the efferent nerves for a considerable time after the initial afferent impulse has subsided, the after-images and the self light may likewise be seen for even long periods, projected as it were against the area of the retina in which the active nerves terminate.

THE DUPLICITY THEORY

The duplicity theory of von Kries assumes the cones to be the retinal organs of photopic and the rods of scotopic vision. In support of the theory many facts of vision have been adduced which have been summarized by Parsons[38] and also by Nagel.[39]

The change in slope of the Porter graphs when only two branches were known has been considered to be strongly confirmatory of the theory, the α branch being due to rod vision and the β branch to cone.

In the writer's experiments all branches of the Porter graphs were obtained on the same central area of the retina where rods are fewest in number or are altogether absent, the flickering at the point of fixation being specially noted. The presence of α branches in the graphs obtained under these conditions is therefore quite adverse to the theory.

The larger number of branches of the Porter graphs and their identification with enhancing and depressing reflex actions seem to remove the graphs completely from their support of the Duplicity theory. The rise of the depressing nervous impulses to predominance over the enhancing when the brightness of the light falls through the first inflexion point to α intensity, shows that the reflex depressing actions are quite sufficient to account for the peculiarities of the Porter graphs, and suggests that the facts of scotopic vision may be explained without the necessity of an additional theory.

If we assume that at very low intensities every stimulus excites the three primary sensations equally, the achromatic interval of vision seems to be fully explained.

The phenomenon of night blindness may be accounted for by assuming that with light intensities below the first inflexion point, the depressing impulses become so large that they are inhibitory in character, while the enhancing impulses are suppressed. This is equivalent to saying that the threshold of vision is raised.

RECIPROCAL INNERVATION

From his study of the muscular movements of the body Sherrington[40] has deduced a principle of fundamental physiological importance and of wide application. For the present purposes this principle may be described by quoting from Hartridge[41] and from Bayliss.[42] The former says: "Sherrington has shown that in the case of muscles there is what is called reciprocal innervation. Thus stimulation of the cortex which causes the contraction of one muscle also brings about a corresponding relaxation of its antagonist, in order that a rapid and economical motion may take place. The contraction and corresponding relaxation are therefore analogous to the response of one part of the retina, which is acctompanied by an inhibition of the surrounding parts of the retina to nhe same kind of stimulus (simultaneous contrast). In a similar malner the inclination to extension which is found to accompany the prolonged flexion of a limb, finds its analogy in the phenomena of after images and adaptation of the eye, since the tendency is to suppress a similar stimulus in the part of the retina stimulated and to encourage its complementary. The inference to be drawn from these analogies is that the after-image and its allied phenomena are caused by changes in the conducting paths of visual impressions which are similar to those found to exist in paths belonging to the motor system. What the nature of these changes in conducting paths may be is at the present time undecided."

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[38] Color Vision, 2nd Ed., p. 215.

[39] Helmholtz, Physiological Optics, Eng. Trans., *2*, p. 343.

[40] Integrative Action of the Nervous System.

[41] Human Physiology, Starling, 3rd Ed., p. 574.

[42] Principles of General Physiology, 3rd Ed., pp. 494 and 498

Bayliss says: "When there are two sets of muscles acting on a movable organ, such as the eye or a part of a limb, in such a way that they antagonize one another, it is clear that, for the effective performance of a particular reflex movement, any contraction of the muscles opposing this movement must be inhibited. Further, the inhibition of the one group must proceed *pari passu* with the excitation of the other group to ensure a well-controlled and steady motion."

"The study of the phenomenon of double reciprocal innervation, as Sherrington points out, shows the importance of inhibition, not only as suppressing excitation, but as a delicate adjuster of the intensity of reflex contraction, a method which is probably of frequent occurrence in natural movements."

The experimental results of the present writer show that stimulation of the cortex evokes the opposing actions of enhancement and depression of the receptor sensitiveness. This has been proved to proceed from one eye to the other, from one retinal area to another, and to occur in the area stimulated. The same phenomena have been found in other senses also. The description of reciprocal innervation just given will apply *mutatis mutandis* to sensory reflexes by substituting the sensory processes of enhancement and depression for contraction and relaxation. The importance of the depressing action may likewise be compared with Sherrington's estimate of the importance of inhibition.

The conclusion of the writer is that sensory activities are based upon the principle of reciprocal innervation, thus giving that principle the widest possible generality of action.

COLOR THEORY

The results of the present investigation are fully in harmony with the trichromatic theory of Young, though they extend the theory materially in many directions. Hering, however, had perceived that retinal areas reciprocally affected each other, and that opponent actions exist in the visual apparatus. The former effect he could not account for, and the latter were assumed to be innate in the colors themselves. By sensory reflex action, it is now proved, the retinal areas and the two eyes reciprocally influence each other; and the opponent actions are found in the opposing processes of enhancement and depression. These, however, are quite harmonious with Young's simpler theory; and therefore in some measure the two great rival theories of color vision may be reconciled.

Since monocular retinal areas influence each other precisely as do the binocular retinae, we may regard the two eyes as a single extended retina with the central unnecessary and inconvenient portion eliminated.

I desire to record my thanks to the Research Council of Canada, with whose financial assistance this investigation has been conducted.

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THE SENSATIONS OF TEMPERATURE, PAIN, AND PRESSURE
By FRANK ALLEN and P. A. MACDONALD. From the Department of Physics, University of Manitoba, Winnipeg. (With six figures in the text.)

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THE SENSATIONS OF TEMPERATURE, PAIN, AND PRESSURE.

By FRANK ALLEN and P. A. MACDONALD. From the Department of Physics, University of Manitoba, Winnipeg. (With six figures in the text.)

(*Received for publication 5th July 1926.*)

IN a series of communications to this and other journals by ALLEN and his associates, the sensations of vision (1), sound (2), touch (3), and taste (4) have been studied by the method of determining the critical frequency of stimulation of the sense organ under various conditions. In this method the sensory receptors are stimulated by an appropriate stimulus, which is periodically interrupted by a rotating disc. The frequency of interruption is adjusted to the point at which the separate impulses become fused into a just continuous sensation, which is termed the critical frequency of interruption. This point can be chronographically determined with precision for various intensities of stimulation. The values of the time during which the stimulus acts at the critical frequency of interruption, when plotted against the logarithms of the intensities of the stimuli, form a graph whose equation is one of those given below.

The investigations carried out by this method have shown most striking similarities in the behaviour of the nervous actions involved in the various senses. Among them are the phenomena of depression and enhancement of sensitivity of the receptors, and the reciprocal influence of portions of the sense organ, or of groups of receptors, upon each other. Perhaps the most conspicuous feature of the identity of sensory actions is the general conformity to what may be termed the Porter equation, since that investigator discovered it in his study of vision.

This equation takes slightly different forms in the various senses, which are as follows:

$$\frac{1}{D} = k \log I + C \quad \text{(Vision)}$$

$$\frac{1}{D} = -k \log I + C \quad \text{(Taste)}$$

$$D = k \log I + C \quad \text{(Sound)}$$

$$D = -k \log I + C \quad \text{(Touch).}$$

In these equations D is the time during which the stimulus acts at the critical frequency of interruption, I is the intensity of the stimulus employed, and k, which may be positive or negative, and C are constants which depend on the nature of the sense and the mode of stimulation. It is significant that these equations comprise WEBER'S and FECHNER'S laws.

The uniformity found to exist in the four senses mentioned indicated the probability that all sensory actions followed the same laws. On this account it seemed desirable to investigate the various cutaneous sensations, and in this communication are given the results of brief studies chiefly of the sensations of temperature and pain by the same general method. In carrying out this work unexpected difficulties were encountered, and the results therefore are not so extensive as those previously obtained with the other senses.

THE TEMPERATURE SENSE.

In the first attempts to investigate the temperature sense a jet of air was used which was heated to any desired degree by passing it, at one time, through a long coil of copper tubing immersed in a water-bath, and, at another time, by electric heating, and then directed upon one of the lips a few millimetres away. The stream of air rendered intermittent by the rotating disc was kept at a very low pressure, so that the temperature effect might be distinguished from the pressure variations and the attention concentrated upon the former. The sensation of warmth was readily evoked, but even an air temperature as high as 80° C. failed to yield a flickering sensation with a motor speed as low as one revolution per second. The temperature receptors apparently are sluggish in their action, and do not seem to react with sufficient rapidity to exhibit the phenomena of critical frequency of stimulation. A second attempt to obtain temperature "flickering" was made by using two air-jets focussed on the same spot on the lip. One jet was hot and the other cold, and by using two sets of open sectors in the same disc they were interrupted alternately. Even under these conditions measurable flickering was unobtainable. In this experiment probably two different sets of receptors were used; and even if it had been successful it would not have been of much value.

Attention was then directed to the possibility of producing stimulation of the thermal receptors by an intermittent electric current. After various trials some success was obtained in eliciting the sensations of warmth, cold, pressure, and pain. This method of stimulation was used in studying the sensations of taste, but these were evoked by the electrolytic products of the current and not immediately by the current itself.

In using the electric method upon the temperature sense it was noted that there is a definite frequency of interruption of the stimulating current above which no sensation is experienced. Experiment showed that this frequency varied with the strength of the current, and therefore gave promise that a series of measurements might be obtained which would permit comparison with other sensory actions.

The arrangement of the apparatus is shown in fig. 1. A continuous electric current was supplied by a large storage battery, A, with a maximum electromotive force of 110 volts. Any desired fraction of this voltage was obtained from a rheostat, B, and the current was conducted through a millivoltmeter callibrated as an ammeter, C, then through the metal water-basin, D, into the arm of the experimenter, E, then through the interrupting disc, F, which rendered the current intermittent, and finally through another controlling rheostat, G. The disc was that used in the investigation on taste which has been referred to above, and its speed, and therefore the duration of the interrupted pulses of current, was measured by a chronograph.

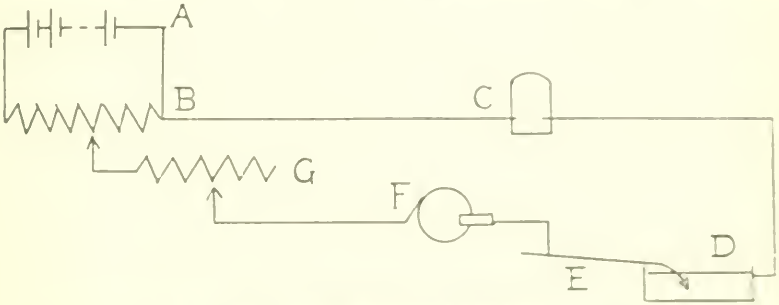

FIG. 1.—Diagram of apparatus.
A, storage battery; B, rheostat; C, ammeter; D, basin; E, arm; F, interrupting disc; G, rheostat.

In using the apparatus a small metallic electrode one centimetre in diameter was covered with blotting-paper moistened with ordinary water and pressed against the back of the right hand near the wrist-joint. The hand was immersed in water in the metal basin, and so completed the circuit. The water was at a temperature of about 23° C. When the temperature was below 20° C. there did not appear to be sufficient contrast between the temperature of the water and the sensation of cold evoked by the current to enable accurate measurements to be made.

When these arrangements were completed the motor was brought to its maximum speed, the circuit through the hand was closed, and the rheostat adjusted to give the desired current, which is very small. The speed of the motor was then gradually reduced by the brake until at some critical value a sensation of cold suddenly appeared under the small electrode. The chronograph circuit was then closed and the speed of the motor recorded. The measurements were repeated at intervals for as many different current-strengths as the physiological conditions permitted. The sensation of cold does not cover the whole area of the skin under the electrode but is localised at one point.

The readings obtained on the arm are given in Table I., and are shown graphically in fig. 2. The abscissæ are logarithms of the current-strength, and the ordinates are the corresponding values of the duration of one current impulse at the critical frequency of interruption at which the sensation of cold appears. The figure contains eleven graphs determined by various small numbers of measurements. These were obtained on different days and doubtless on different nerves. Each graph probably represents the response of an individual nerve, and their relative positions indicate that the receptors for cold vary distinctly in sensitiveness (5). Probably this is true for receptors in all the senses; but in most cases, as for example in vision, the stimuli employed excite simultaneously a considerable number of receptors, and the average result is constant in value.

TABLE I.—SENSATION OF COLD. LEFT WRIST.

	Current I.	Log I.	D.		Current I.	Log I.	D.
	Ampere.		Sec.		Ampere.		Sec.
A	0·00272	$\bar{3}$·435	0·00888	G	0·00227	$\bar{3}$·356	0·00440
	00317	·502	·00755		·00249	·397	·00413
	·00408	·611	·00590		·00272	·435	·00382
	·00544	·736	·00413		·00295	·469	·00350
					·00499	·698	·00178
B	0·00317	$\bar{3}$·502	0·00563				
	·00453	·657	·00390	H	0·00227	$\bar{3}$·356	0·00415
					·00340	·532	·00275
C	0·00249	$\bar{3}$·397	0·00623		·00408	·611	·00213
	·00317	·502	·00513				
	·00385	·586	·00425	I	0·00159	$\bar{3}$·201	0·00475
					·00227	·356	·00343
D	0·00227	$\bar{3}$·356	0·00588		·00317	·502	·00245
	·00272	·435	·00515		·00453	·657	·00135
	·00317	·502	·00456				
	·00385	·586	·00373	J	0·00227	$\bar{3}$·356	0·00288
	·00544	·736	·00225		·00295	·469	·00238
E	0·00227	$\bar{3}$·356	0·00520	K	0·00181	$\bar{3}$·259	0·00300
	·00317	·502	·00380		·00215	·333	·00275
	·00408	·611	·00285		·00272	·435	·00225
	·00453	·657	·00268				
F	0·00283	$\bar{3}$·452	0·00390				
	·00317	·502	·00360				
	·00453	·657	·00225				
	·00521	·717	·00188				

Each graph consists of a single straight line with no indication of a second branch. There is, however, a noticeable convergence of the graphs towards the right, that is, towards the higher values of the current strength.

A similar series of measurements of the cold sensation was made upon the right leg, the electrode being placed some distance above the ankle. A wet bandage placed just above the ankle was in this case substituted for the basin as the second electrode. The measurements are given in Table II., and are shown graphically in fig. 3. The seven graphs are of the same character as those for the arm, but while the time-intervals are about the same, the current strengths are only about one-half of those in the arm. This indicates that the cold receptors in the leg are probably about twice as sensitive as those in the wrist. This is possibly the result of exposing the latter and covering the former with clothing.

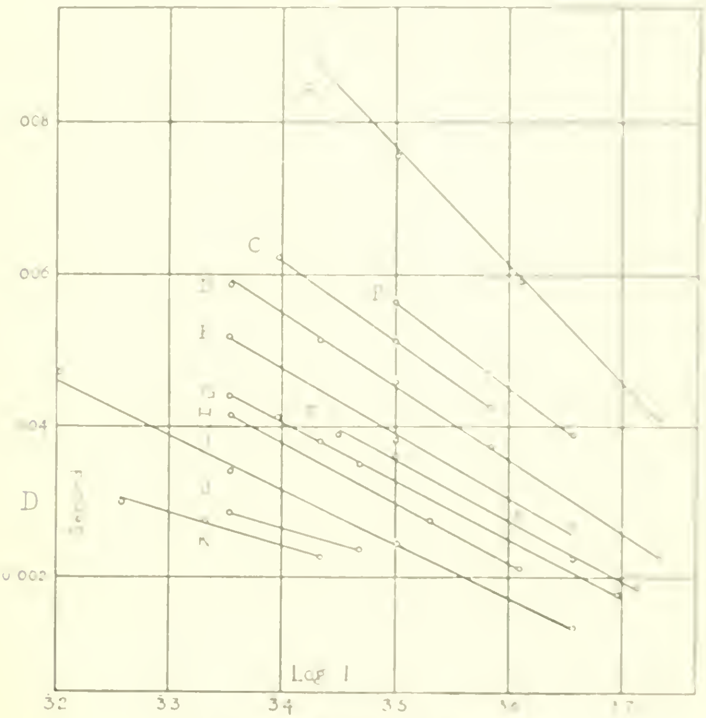

FIG. 2.—Cold sensation. Left wrist.

In the figure, two of the graphs, marked D and E, show distinct second branches at sensitivities lower than the measurements obtained on the receptors in the arm. Further, it seems likely that the two lowest graphs, F and G, consist of lower branches without the upper.

We may conclude, therefore, that the graph representing the response

TABLE II.—SENSATION OF COLD. RIGHT LEG.

	Current I.	Log I.	D.		Current I.	Log I.	D.
	Ampere.		Sec.		Ampere.		Sec.
A	0·00204	$\bar{3}$·310	0·00323	E	0·00093	$\bar{4}$·968	0·00313
	·00249	·397	·00238		·00113	$\bar{3}$·054	·00215
					·00136	·134	·00150
B	0·00091	$\bar{4}$·958	0·00565		·00159	·201	·00133
	·00113	$\bar{3}$·054	·00485		·00181	·259	·00125
	·00159	·201	·00350				
	·00181	·259	·00300	F	0·00113	$\bar{3}$·050	0·00164
					·00125	·096	·00145
C	0·00091	$\bar{4}$·958	0·00518		·00136	·134	·00120
	·00177	$\bar{3}$·248	·00233		·00153	·185	·00095
	·00181	·259	·00240				
				G	0·00091	$\bar{4}$·958	0·00165
D	0·00091	$\bar{4}$·958	0·00445		·00113	$\bar{3}$·054	·00138
	·00113	$\bar{3}$·054	·00370		·00118	·072	·00140
	·00136	·134	·00295				
	·00198	·298	·00175				
	·00204	·310	·00168				
	·00227	·356	·00145				

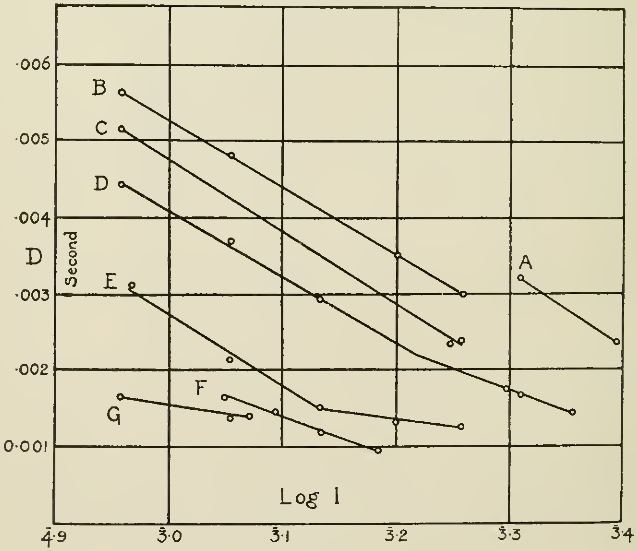

FIG. 3.—Cold sensation. Right leg.

of each receptor for the cold sensation, when stimulated through a wide range of intensities, consists of at least two branches. These conform to the equation

$$D = -k \log I + C,$$

which is identical with that obtained in touch where the pressure of the air was used instead of the electric current.

It is noteworthy that the values of the duration of the stimulus at the critical frequency of interruption are of the same magnitude as those obtained in the experiments on touch.

It may be remarked that no sensation of warmth was evoked by the above method of stimulation. However, by using a point electrode, as described below, this sensation was elicited, but it was never distinct enough in our experiments to yield measurements.

THE PRESSURE SENSE.

By varying the experimental conditions the pressure sense could also be evoked by the same method. For this purpose a wet bandage placed around the wrist served as one electrode, and one finger, the second on the left hand, dipped in the water in the metal basin was the other. With a high-frequency of interruption of the current no sensation was perceptible. On decreasing the speed of the motor, however, a point was reached at which a sensation of pressure was felt. With further decrease in speed this sensation ceased, but still further decrease caused the sensation to be renewed. These phenomena appear to correspond to the two tactile sensations, the superficial and the deep-touch, formerly described in the papers to which reference has been made. The motor was incapable of giving sufficiently high speeds for the deep-touch sensation to be obtained with all current intensities, so that the values given in Table III. are probably for the superficial tactile sensation.

TABLE III. SENSATIONS OF PAIN AND PRESSURE.

	Current I.	Log I.	D.		Current I.	Log I.	D.
	Ampere.		Sec.		Ampere.		Sec.
A	0·00091	$\bar{4}$·958	0·01125	B	0·00136	$\bar{3}$·134	0·01500
Pain	·00120	$\bar{3}$·080	·00688	Pain	·00159	·201	·00950
Left Hand.	·00138	·141	·00475	Right Leg.	·00181	·259	·00350
	·00168	·225	·00463		·00204	·310	·00290
	·00181	·259	·00395		·00227	·356	·00245
Pressure.	0·00068	$\bar{4}$·833	0·00144	Unknown	0·00136	$\bar{3}$·134	0·00125
	·00093	·968	·00113	Nerve.	·00159	·201	·00113
	·00113	$\bar{3}$·054	·00094		·00181	·259	·00105
	·00136	·134	·00078		·00198	·298	·00095
					·00213	·329	·00090

The sensation produced feels as if the immersed part of the finger were being squeezed with an even pressure on all sides. There is also experienced at the same time a tingling sensation similar to that obtained when the ulnar nerve at the elbow is sharply struck.

The four measurements taken are plotted in the graph in fig. 4, which has two branches. As both branches are determined by only two points, it is not proved that each would be a straight line if more readings had been obtained. It is probable, however, that the branches are straight lines like those found in other sensory actions. The graph conforms to the same equation that was given above, but the values of the time-intervals are much smaller than those obtained by the use of the jet of air.

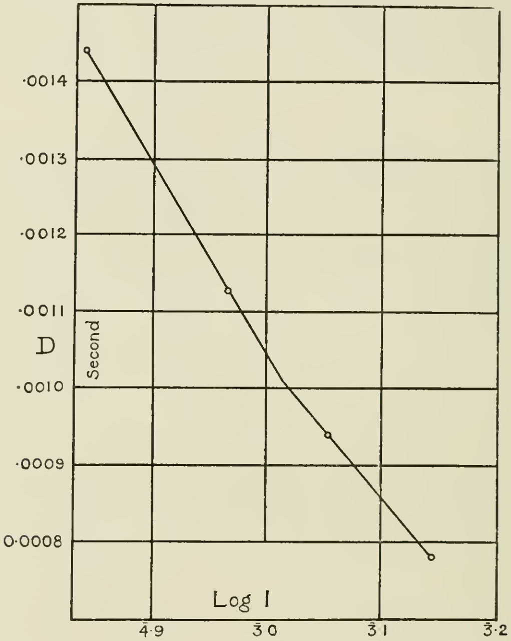

Fig. 4.—Pressure sensation.

The Sensation of Pain.

Sensations of pain may be evoked in the same manner as cold. On decreasing the speed of the motor the cold sensation appears first at a certain critical frequency of interruption of the current, and with further decrease the pain sensation is produced. It is evident, therefore, that the receptors of the latter sensation are not quite as responsive to intermittent stimulation as those of the former.

For the sensation of pain two sets of readings have been obtained, one for the hand and the other for the leg. A wet bandage was placed on the left wrist as one electrode, and the second finger partly immersed in water in the basin was the second. The cuticle was pulled away from the base of the nail, leaving only a very thin layer of skin covering the flesh. In this sensitive area a superficial pain sensation like a sting may be evoked which is localised in an area about the size of the head of a pin. The measurements are given in Table III., and are shown graphically in fig. 5, A. The graph possesses two distinct branches.

A similar set of readings was obtained on the front part of the leg. The electrode was pressed against the skin above the ankle over the shin-bone, and a wet bandage lower down completed the electric circuit. Two pain sensations appear to exist, one at the surface of the skin and the other near the bone. The latter, though not sharply defined, was extremely painful, as if one had received a blow on the part under the electrode. The measurements obtained for the deeper sensation are also given in Table III., and are shown in fig. 5, B. This graph also has two branches. Both graphs also conform to the equation which was given above. The relative positions of the two graphs in the figure show clearly that the pain sensation in the finger was elicited by much weaker electric stimulation than that in the leg. As, however, the finger was rendered specially sensitive and the leg was in its normal condition, the measurements do not indicate the relative sensitivities of the two sets of receptors.

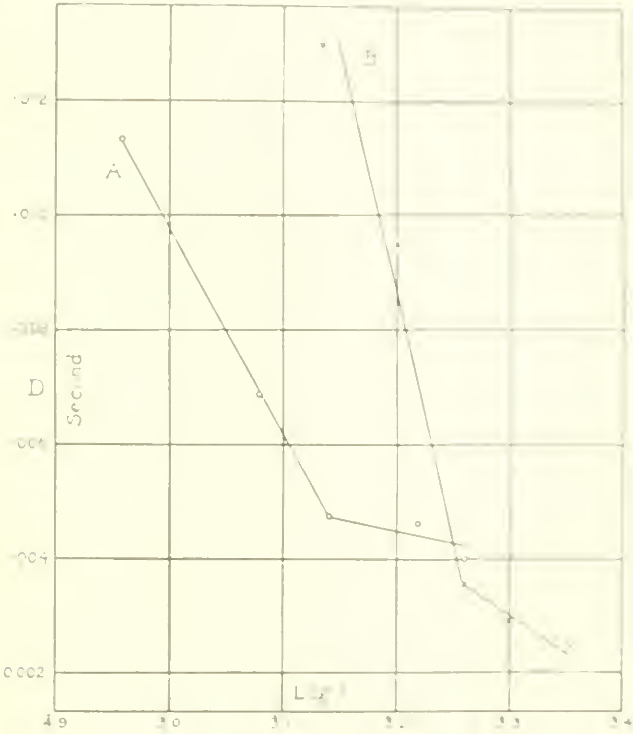

Fig. 5.—Pain sensation.

A. Left hand. B. Right leg.

NERVES OF UNKNOWN NAME.

Certain nerves of unknown name running to the hand near the surface of the skin on the wrist may also be stimulated. These do not give rise to any ordinary sensation, but at a certain critical frequency of stimulation the impression is given that they have started to vibrate under the skin. A series of measurements was obtained for this phenomenon, which are given in Table III., and are shown in fig. 6. The five readings lie along a single straight line, which also conforms to the equation representing the graphs already discussed.

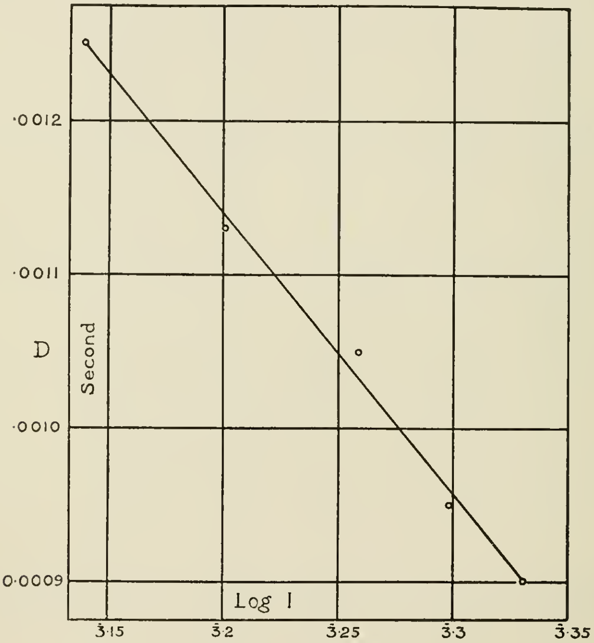

FIG. 6.—Unknown nerve.

By using a fine platinum wire in a drop of water for one electrode, and the hand immersed in the water in the basin for the other, individual points of all kinds may be examined by this method of intermittent stimulation. The electrode in a drop of water around each hair invariably evokes a pain sensation of the same type as that obtained at the base of the nail. Cold, warm, and pressure spots may also be found accompanied by most decided sensations. The first time pressure was evoked the sensation was so realistic that for a moment it seemed as if a solid object was being forced against the surface of the skin. Attempts to obtain series of measurements with this method were unsuccessful, as the current rapidly destroyed the skin, and it was impossible to maintain it long enough to obtain readings.

CONCLUSIONS

The graphs for the four kinds of cutaneous sensations discussed above are all of the same type, consisting in their entirety of at least two branches. These correspond exactly to the first and second branches of the graphs obtained for the tactile sensations by ALLEN and WEINBERG (3). Probably if the measurements could have been extended over greater ranges of current intensities a third branch would have been found, as in the senses of vision, touch, and taste. The graphs all conform to the same equation found for the sense of touch:

$$D = -k \log I + C.$$

The order of magnitude of the times of duration of the stimulus at the critical frequency of stimulation is also the same for all the sensations discussed in this paper, and for touch. We may conclude, therefore, that all the cutaneous sensations obey the same fundamental laws. In the equations to the graphs the constants k and C have different values for the two, or more, branches and they are different for the different sensations. The negative sign for k indicates that the duration of the stimulus at the critical frequency of stimulation diminishes as the intensity of the stimulus increases.

The measurements obtained in these investigations, as far as we can judge, are the normal values for the receptors indicated. No measurements under the conditions of depression and enhancement of sensitivity seemed possible, as there was no certainty that the same receptors were stimulated on different occasions. There can be no doubt, however, that both processes are in operation in all these sensations. The interpretation of the two-branched graphs most probably rests upon the functions of the sensory reflex actions involved. In other researches on the sensations of vision, touch, and taste, experiment justified the conclusion that in each sense reflex actions of two kinds existed, one of which depressed and the other enhanced the sensitiveness of the receptors. It is a sudden change in the ratio of these two processes that causes a corresponding alteration of the sensitivity of the receptors and thereby of the slope of the graph.

In the sense of touch it was found that stimulation of low intensities corresponding to the uppermost branch of the graph elicited enhancement in excess of depression, while higher intensities of stimulation caused the reverse. Since the other cutaneous sensations are found to conform to the same equation, it may be inferred that the results of stimulation will also be similar. Experience under pathological conditions also testifies to the existence of enhancement and depression of receptor sensitivity in the senses of temperature and pain.

This investigation is one of a series of researches relating to colour-vision and other sensory actions now being conducted under the direction of Professor Frank Allen, with the financial assistance of the National Research Council of Canada, to which body we desire to express our thanks.

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